Utilizing Aquaculture Effluent Efficiently in Cucumber Production through Substrate Choice and Fertigation Management

by

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Abstract

De-coupled aquaponics offers several benefits over coupled aquaponics due to ability to manipulate each sub-unit independently. Fine-tuning plant production practices to make the best of the low-nutrient laden aquaculture effluent (AE) is important for optimizing the system. The studies in this dissertation were aimed at providing data-based evidence for substrate choice and timed fertigation to managing AE especially in a decoupled aquaponics system where nutrients do not recirculate between the hydroponic and aquaculture components. A meta-analysis of crop yield comparisons between hydroponics and aquaponics showed that nutrient supplementation was necessary to bring aquaponics crop yields to par with or even above conventional hydroponics. Variability in aquaponics crop yield comparisons was explained by a myriad of factors including substrate choice. Substrate choice trials were conducted to assess performance of cucumber by pine bark and perlite substrates at two densities. The results showed no overall yield difference between the two substrates. However, better cucumber yields were recorded by pine bark in one plant than in two plants per pot. In separate experiments, fertigation management was assessed by scheduling (1) fertigation intervals at 15, 30, 60, and 90 minutes at a fixed duration of 4 minutes, or (2) fertigation durations at 1, 2, 3, or 4 minutes at a fixed interval of 30 minutes in conventional hydroponics. In another sets of experiments, effect of fertigation duration as described above was assessed with sole and supplemented aquaculture effluent (AE). The results showed that there was no significant effect of interval on cucumber yield leading to significantly higher water use efficiency for the highest fertigation interval of 90 minutes. Differential nutrient partitioning to leaves, shoot and fruits was observed for each interval with more sulfur partitioned to leaves at 30 minutes and more boron partitioned to fruits at 60 minutes. However, due to the reduced leachate volume with increasing interval, and increasing cucumber water use efficiency with increasing fertigation interval, fertigating every 90 minutes for a 4-minute duration offered the best results. When fertigation interval was maintained at 30 minutes, results show that a duration of 1 minute was sufficient to promote cucumber growth and yield. Fertigation trial with sole and supplemented AE showed that plants fertigated with supplemented aquaculture effluent (AE) leached out on average up to 56% and 41% more EC and nitrate N, respectively than those fertigated with sole AE. Fertigating for only 1-minute duration with sole and supplemented AE resulted in significant yield reduction whereas fertigating for 3 minutes generally promoted higher yields and total aboveground biomass but was not statistically far from yields obtained by fertigating for 1 minute. Comparing supplemented and sole AE, only a 7% higher yield was obtained due to nutrient supplementation. Therefore, under the current condition, use of sole AE was adequate to obtain desirable yields of the cucumber plants. The management practices tested in this dissertation, substrate choice and fertigation management, provide practical solutions that can be used with decoupled aquaponics systems.

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List of Abbreviations

AE	Aquaculture Effluent
FAO	Food and Agriculture Organization of the United Nations
CEC	Cation Exchange Capacity
LAI	Leaf Area Index
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SLA	Specific Leaf Area
SPAD	Soil Plant Analysis Development
WWAP	World Water Assessment Programme of the United Nations

Chapter 1

1.0 Introduction

The multi-trophic combination of recirculating aquaculture system and hydroponics is also known as aquaponics (Rakocy, 1988). This integrated fish-plant production system is intimated to contribute to sustainable food production for both urban and global needs whilst reducing environmental pollution and need for resources (Goddek et al., 2015). Resources such as water are depleting due to climate change, when coupled with growing demand for such finite resources becomes a challenge to human survival. Demand for water in agriculture alone accounts for about 70% of water use globally (WWAP, 2017) or up to 90% in arid areas such as North Africa (FAO, 2005). Therefore, systems that employ an integrated approach in which water is re-used, and waste is recycled have great benefits for sustainability, and contribute to minimizing environmental pollution. Aquaponics is a rapidly growing and accepted system of plant production as interest has grown exponentially in recent years (Love et al., 2014). However, there are still debates on appropriate use of the term ‘aquaponics’. It has been argued that ‘aquaponics’ *sensu stricto*, only refers to a system where 50% of plant nutrients are obtained from aquaculture effluent (Palm et al., 2018). Irrespective of terminological semantics, two aquaponics system types based on material flow are generally reported in the literature namely coupled also called ‘single loop’, and decoupled also known as multi-loop aquaponics (Goddek et al., 2016; Palm et al., 2018). Aquaponics system type plays very important roles on the choice of practices that can be adopted (Palm et al., 2018). For instance, in decoupled or a multi-loop aquaponics system in which nutrient-rich effluent movement is unidirectional (**Figure 1**), it is easy to modify production factors of the hydroponic subunit without affecting the aquaculture subunit. Aquaculture effluent pH modification (Blanchard et al., 2020), and nutrient supplementation (Delaide et al., 2016) have been successfully achieved in the hydroponic subunit of decoupled systems without affecting the aquaculture subunit.

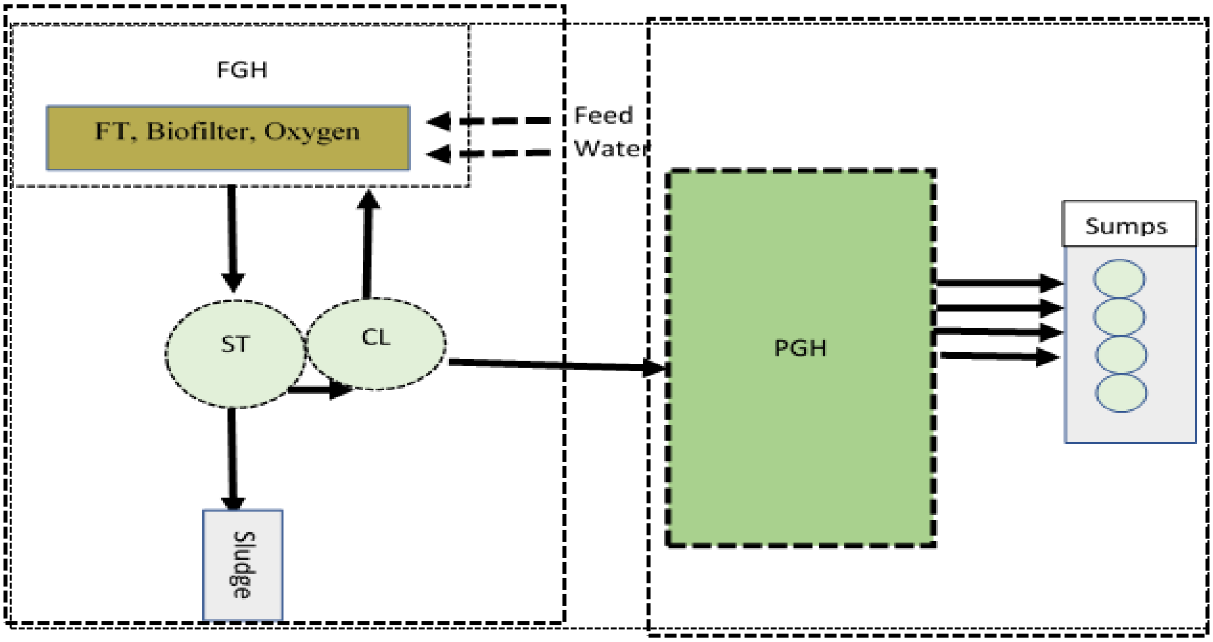

Figure 1. Schematic of a decoupled aquaponics system used in Chapter II study. ST=settling tank (clarifier 1), CL=clarifier 2, PGH=plant greenhouse, FGH=Fish greenhouse, FT=Fish tank.

One of the key challenges to multi-loop or decoupled aquaponics systems is water losses through evapotranspiration. Evapotranspiration rates are irreversible and also crop dependent with comparative trials indicating differences between cucumber which recorded the second highest after tomato for evapotranspiration (Graber and Junge, 2009). Evapotranspiration rates are shown to drive aquaculture water quality in a theoretically simulated model of a decoupled aquaponics system (Goddek et al., 2016) due to effect on refill rates. Remedies to water losses have been suggested to include proper system sizing of the hydroponic cultivation area based on phosphorus availability (Goddek et al. 2016). Also, studies show that up to 85% of the total irrigation water condenses during air cooling process on heat exchangers and can be redirected to the nutrient solution without concern (Kloas et al., 2015; Teitel et al., 2012). However, these advance techniques are usually not practically available to small-scale growers. Therefore, for now, it is essential that water losses be minimized through effective fertigation scheduling to deliver both adequate water and nutrients at the same time using simple automated systems such as timer clocks.

Nutrient concentrations in aquaculture effluent are generally lower than in conventional hydroponics systems (Bittsánszky et al., 2016) and contain only approximately 25% of the plant nutrient requirements (Lastiri et al., 2018). Therefore, effective substrate choice and fertigation management would offer simple but practical solutions to use of aquaculture effluent. Previous studies achieved similar or better crop yields in aquaponics versus conventional hydroponics through nutrient supplementation (Delaide et al., 2016). However, there is sufficient evidence that good foliar nutrient sufficiency and yields in aquaponics can be achieved without nutrient supplementation (Blanchard et al., 2020) especially when using aquaculture effluent from biofloc rather than clear water aquaculture systems (Pinho et al., 2021, 2017).

Differences in minerals solubilization rates results in unequal accumulation of nutrients in the aquaculture effluent (Rakocy J. and Hargreaves, 1993; Seawright et al., 1998) coupled with losses through immobilization, adsorption and precipitation mechanisms, leaching, runoff, and volatilization leading to their unavailability for plant use (Wongkiew et al., 2017) if appropriate substrate is not used. Therefore, depending on type of substrate used and volume of fertigation solution supplied, losses might be exacerbated. Nitrogen (N) losses for instance can be accelerated at increasing pH (Tyson et al., 2007; Zou et al., 2016), lowering dissolved oxygen (Fang et al., 2017) and lowering microbial population (Wongkiew et al., 2018). Other studies have shown that plant species plays a major role in N loss for aquaculture effluent use (Hu et al., 2015; Wongkiew et al., 2018). Increased pH is also known to affect phosphorus availability due speciation (dissociation) of the nutrient at high pH (Cerozi and Fitzsimmons, 2016). Therefore, effect of pH on nutrient availability has been a focus for both couple (Tyson et al., 2007; Zou et al., 2016) and decoupled (Blanchard et al., 2020) aquaponics systems and outside the scope of this dissertation. However, choice of inherently low pH substrates such as pine bark of between 4.1 to 5.2 (Maher et al., 2008; Boyer et al., 2012) could serve as a potential pH regulator in aquaponics. Nevertheless, pine bark has potential effect on N immobilize and microbial respiration (Boyer et al., 2012) which affect nutrient availability to plants especially when not properly aged.

Aside the challenges listed above, nutrients are also lost in the fish sludge by getting bound in the solids with up to 13% of P input being lost through unaccounted forms (Cerozi and Fitzsimmons, 2017). Nutrients bound up in fish sludge are recoverable through mineralization using upflow anaerobic flow blankets techniques (Goddek et al., 2018) or biologically aerated filters (Zhang et al., 2020). Through nutrient mineralization approaches, concentration of nutrients in the aquaculture effluent is improved and when coupled with appropriate substrate and fertigation scheduling could lead to increased water and nutrient use efficiency in aquaponics.

The use of soilless cultivation systems has been preferred over soil-based systems in aquaponics due to known problems associated with the soil (Hussain et al., 2014). Soilless growing media are also easier to handle and provide a better growing environment compared to soil-based systems (Mastouri and Hassandokht, 2005). Additionally, control of water availability, pH and nutrient concentration in the root zone is easier in soilless systems than soil-based systems (Epstein and Bloom, 2005).

Cucumber (*Cucumis sativus* L.) was chosen as the test crop for this study due to the versatile nature of the crop. Cucumbers can grow in most environmental condition, and cultivated broadly worldwide (Soleimani et al., 2009). Cultivation of cucumbers covers both field and greenhouse but greenhouse cultivation extends the growing cycle, through off-season cultivation and offers higher economic return (Chandra et al., 2000). Greenhouse cultivation especially in soilless systems also offers better quality and yield than open field cultivation (Jovicich et al., 2007). However, cucumbers are generally thermophilic and are susceptible to frost (Bacci et al., 2006). Best growing temperature for cucumber range from above 22.0°C to below 27.0°C (Singh et al., 2017). Conditions of high humidity, high light, sufficient nutrition, and soil moisture increase cucumber productivity especially in plastic greenhouses (El-Aidy et al., 2007). Cucumbers can be direct-seeded or grown using transplants. Optimum row spacing for increased productivity is 1.20 and 1.5 m with intra-row spacing of between 0.30 and 0.45 m. Using suitable intra-row spacing and pruning results in higher fruit yield of the crop (More et al., 1990). Cucumber is cultivated for its tender fruits, consumed either raw as salad, cooked as vegetable or pickled in its immature stage (Sumathi et al., 2008). Harvesting for fresh consumption is done when fruits are fully grown but before physiological maturity (Kanellis et al., 1986).

Research Justification

Substrate choice and effective fertigation management plays an essential role in achieving minimal wastage and low discharge especially in drain-to-waste systems. For fertigation, using a timer-clock to schedule fixed fertigation intervals and/or duration is a simple automation process that relieves farmers of extra labor for fertigation. However, need to change timing daily to meet evapotranspiration demands of the crop and achieve recommended drainage fractions derails this automation benefit. Although advancement in technology has led to availability of weather monitoring systems that could be used for irrigation and/or fertigation management, a timer-clock is still preferred due to its simplicity. Aquaponics that combines recirculatory aquaculture system with hydroponic techniques requires effective management of the effluent to achieve desired plant productivity. Therefore, a combination of production management techniques is required to achieve the objective of meeting crop demand and reducing environmental pollution which is the main goal of aquaponics.

The studies conducted in this dissertation therefore sought to manage fertigation nutrient solution from aquaculture effluent, and hydroponic solution using substrate and plant density manipulations, fertigation amount through adjusting intervals and duration on greenhouse-grown soilless cucumber. Therefore, the broad objectives of the research were to 1) assess the comparative yield performance of aquaponic and hydroponic crops, 2) determine optimal substrate and density for cucumber yield when fertigated with aquaculture effluent, 3) determine effect of timed fertigation interval or duration on growth, tissue nutrient content, and yield of cucumber, and 4) identify optimal fertigation duration for yield and other agronomic traits of cucumber fertigated with aquaculture effluent, with and without nutrient supplementation.

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Chapter II

2.0 Literature Review

2.1 Comparisons between Aquaponics and Conventional Hydroponic Crop Yield: A Meta-Analysis

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Abstract: Aquaponics is a relatively new system of farming which has received ardent research attention due to its potential for sustainability. However, there is no consensus on comparability between crop yields obtained from aquaponics (AP) and conventional hydroponics (cHP). Meta-analysis was used to synthesize the literature on studies that compared crop yields of AP and cHP. Factors responsible for differences were also examined through subgroup analysis. A literature search was done in five databases with no time restriction in order to capture any publication on AP and cHP crop yield comparisons. The search was however, limited to publications in English, Journal, and Conference articles. Study characteristics and outcome measures of food crops were extracted. A natural log response ratio effect size measure was used to transform study outcomes. An unweighted meta-analysis was conducted through bootstrapping to calculate overall effect size and its confidence interval. Between-Study heterogeneity (I^2) was estimated using a random effects model. Sub-group and meta-regression were used assess moderators an attempt to explain heterogeneity in the effect size. The results showed that although crop yield in AP was lower than conventional cHP, the difference was not statistically significant. However, drawing conclusions on the overall effect size must be done with caution due to the use of unweighted meta-analysis. There were statistically significant differences between crop yields of at least two of aquatic organism, hydroponic system type and nutrient supplementation used in the studies. Nutrient supplementation particularly led to on average higher crop yield in AP relative to cHP. These findings are vital information source for choosing factors to include in an AP study. These findings also synthesize the current trends in AP crop yields in comparison with cHP.

Keywords: Nutrient supplementation; Hydroponic system type, aquaculture effluent, Subgroup analysis; Log response ratio.

1.1.1 Introduction

Aquaponics is a farming system that integrates a recirculating aquaculture system (RAS) with hydroponics into a single production system (Rakocy J. and Hargreaves, 1993). Conventional Hydroponics (hereafter, cHP) has been described as an intensive cultivation of crops in soilless media, and RAS is intensive farming of aquatic animals (fish, crawfish, shrimps etc). The concept of aquaponics was birthed due to need for nutrient recycling of aquaculture waste (Graber and Junge, 2009). Aquaponics (AP) is suggested to reduce impacts of eutrophication, water usage, and geographic footprint of aquaculture as a result of the symbiotic ecosystem created by integrating aquaculture with HP (Cohen et al., 2018). Aquaponics systems are also proved to be water and nutrient use efficient (Nichols and Savidov, 2012). Aquaponics offers a potential for sustainability in crop production (Belsare et al., 2007; Kloas et al., 2015; Nehar, 2013; Price, 2009; Tyson et al., 2012) by combining the benefits of controlled environment agriculture and nutrient recycling. However, a major constraint to aquaponics sustainability is crop yield comparability between the system and cHP. Since aquaponics is a new system, its acceptance depends on its ability to compete or at least compare well in crop yield cHP. The ability of AP crop yield to compare with cHP depends on several factors which have been examined sparingly in the literature. However, there is still no consensus on how well AP crop yields compare with cHP. Whereas some studies show that aquaponically grown crops have lower crop yields than conventional HP systems (Blidariu et al., 2013; Goddek et al., 2018; Reyes-Flores et al., 2016; Roosta and Hamidpour, 2013), other studies show that higher or similar crop yields could be obtained for aquaponics compared to conventional HP systems (Alcarraz et al., 2018; Anderson et al., 2017; Roosta and Afsharipoor, 2012). Economic assessment of AP sustainability (Love et al., 2015; Palm et al., 2018, 2014) and life cycle assessment has been done elsewhere in the literature (Boxman et al., 2017). Therefore, the aim of this meta-analysis is not to assess the economic or environmental sustainability of aquaponics but crop productivity.

Contrasting reports on AP crop yield comparisons with cHP is due to the rather numerous factors that contribute to crop yield variability in AP. Factors such as fish species, feed protein content, flow rates, aquaculture effluent pH (Zou et al., 2016), fish density (Groenveld et al., 2019), feeding rate (Liang and Chien, 2013), AP coupling type among other factors greatly contribute to variability in nutrient quantity and quality in AP systems thereby affecting crop yield. Generally, aquaculture effluent is usually low in essential crop nutrients required for optimum plant growth warranting the need for nutrient supplementation. Reports show that nutrient supplementation leads to similar or even higher AP crop yield as cHP (Delaide et al., 2016; Goddek and Vermeulen, 2018; Jordan et al., 2018). Other factors that influence AP crop yield include crop species (Buzby et al., 2016; Delaide et al., 2017), substrate/grow media type (Delaide et al., 2017; Roosta and Afsharipoor, 2012; Wortman et al., 2016), HP system type and a myriad of others which affect nutrient availability and uptake by crops (Enduta et al., 2011; Graber and Junge, 2009; U Knaus and Palm, 2017; Pinho et al., 2018; Savidov et al., 2007). A combination of factors from the aquaculture component and HP components interplay to affect crop yields in AP and how they compare with cHP systems. Therefore, comparing crop yields between AP and cHP requires accounting for these factors. Studies that compare AP and cHP are unable to include all these factors in a single experiment due to obvious practical reasons of cost and labor.

Meta-analysis enables the synthesis of all studies that compare AP and cHP and a delineation of factors responsible for any difference between the two systems. Meta-analysis is a quantitative approach used to synthesis research findings (Shorten and Shorten, 2013). The approach allows for an estimation of an effect size which enables comparison across studies with similar research question (Borenstein et al., 2009; Shorten and Shorten, 2013). Effect size can be quantified using various effect size metrics (Borenstein et al., 2009). Due to the quantitative nature of meta-analysis, data from various studies that sought to compare AP and cHP crop yield were combined. Meta-analysis also allowed us to separate the contribution of the factors listed above to the overall crop yield difference. The objectives of this study were to 1. quantify the magnitude of crop yield difference between aquaponics and conventional hydroponics; 2. estimate between study heterogeneity in estimating a summary effect size, and 3. conduct sub-group analysis to account for the heterogeneity in quantifying summary effect size

1.1.2 Methodology

1.1.2.1 Literature search

The search began on 3/4/2019 in Web of Science, CAB Abstracts, Agricola, Aquatic Science and Fisheries Abstracts (ASFA), and ProQuest Dissertations and Theses Global. These databases are known to index aquaponics related publications. The search terms "Aquaponic* AND Hydroponic* AND Crop yield", were used to search Agricola, CAB Abstracts, while "Aquaponic* OR Recirculat* Aquaculture AND Hydroponic*) *AND* **TOPIC:** (crop* yield OR crop* growth OR vegetable*)" were used in Web of Science, ASFA and ProQuest Dissertations and Theses Global. The Boolean truncation (*) was used to capture all variations of the words. The literature search was constrained to publications in English. Reviews and editorial materials were also excluded. Any study that had the words AP and cHP was captured by the search. There was no publication date limitation placed on search range so as not to miss earlier publications related to aquaponics.

1.1.2.2 Inclusion Criteria

The studies were screened based on the criteria described in Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) (Moher et al., 2009). The following criteria were used to screen main text of articles for inclusion: 1. studies that compared AP with conventional HP, 2. conducted on a food crops, 3. contained replicated controlled trials, and 4. reported a mean and at least a sample size. Any measure of variance was not considered inclusion criteria because 1) most studies did not report any measure of variance and 2) the effect size metric chosen for this meta-analysis did not require a measure of variance.

1.1.2.3 Data extraction and processing

Data from included studies were extracted into Microsoft Excel for further processing. Important variables extracted included author(s) first name and year of publication, fish/aquatic species used in the study, mean fish stocking density, protein content of fish feed, type of AP system (Coupled or decoupled), HP system type (media-based, nutrient film technique, or deep-water culture), type of grow media, crop, and whether nutrients were supplemented or not. Categorical design variables were used for subgroup analysis while continuous variables were used in meta-regression. The study outcomes extracted included the sample sizes, mean and variance components (standard deviation (SD), standard error or confidence intervals) of yield and yield components, although the variance measures were not used in the analysis. For leafy vegetables such as lettuce, basil, spinach, etc., shoot fresh weight was used as yield. Studies that presented their data in graphs were extracted using ImageJ (free online software for data extraction) following best practices of the software.

1.1.2.4 Effect size calculation and estimation of overall effect size

In the current study, a log response ratio was chosen due to its ability to accommodate studies that do not report measures of variance such as standard error, confidence interval etc (Borenstein et al., 2009). The effect size measure used was the log response ratio (“Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system,” 2015; LAJEUNESSE, 2011). It is estimated using the equation:

$$\text{lnR} = \ln\left(\frac{Y_{Ap}}{Y_{Hp}}\right) \tag{1}$$

where Y_{Ap}, and Y_{Hp} are the mean yields from the AP and HP systems respectively and lnR is the natural log response. Effect size was transformed back to the response ratio for easy biological interpretation of results. The random-effects model with a restricted-maximum-likelihood estimator (REML) was used to calculate the overall (summary) effect size, its 95% confidence intervals (CIs) and heterogeneity. Estimation of overall effect was done using an unweighted meta-analysis by bootstrapping. The open-source, cross-platform software for ecological and evolutionary meta-analysis (OPENMEE) was used for bootstrapping meta-analysis. Unweighted analysis was adopted to enable inclusion of studies that did not report any variance measure (standard deviation, standard error or CI). Moreover, the calculation of lnR does not require variance measures. In total, 50 effect sizes were obtained from 22 studies.

1.1.2.5 Subgroup analysis and meta-regression

Subgroup analysis was conducted on type of fish/aquatic species, type of AP system, HP system type (media-based, nutrient film technique, or Deep-Water Culture), type of grow media, crop, and whether nutrients were supplemented or not. Subgroup analysis was done using OPENMEE and R metafor package. Results of subgroup analysis were then extracted from the program and plotted using MS Excel. Meta-regression was conducted to determine relationship between effect size and feed protein content, and mean fish stocking density. Meta-regression was done in R (Team, 2018) with the “meta” package. The ‘bubble’ function in the package was used to visualize the meta-regression (see code in appendices). Meta-regression usually assumes a linear relationship between the explanatory variable(s) and the outcome measure where P-values are based on the null hypothesis that the slope of the regression line is zero and significant outcomes simply suggest that the slope significantly differs from zero and that there is a relationship (positive or negative) between the factor and outcome being compared (Buhmann et al., 2015). Subgroup analysis that adopts a meta-regression approach also allows for formal statistical tests for differences between subgroups where they are categorical (Buhmann et al., 2015). However, the current assessment did not adopt meta-regression approach for categorical subgroup analysis but only for the continuous independent variables.

1.1.3 Results

1.1.3.1 Study descriptions

The was a steady growth in number of publications (k used here to distinguish number of studies from number of effect sizes *n*) that compare AP and cHP in a single trial from 2009 to 2018. The distribution of articles for the period are 2009 (*K*=1), 2011 (*K*=10), 2012 (*K*=2), 2014 (*K*=1), 2015 (*K*=1), 2016 (*K*=4), 2017 (*K*=4), and 2018 (*K*=8). The results also showed that tilapia (*K*=8) followed by carp (*K*=6) were the most common fish used in these experiments. Rainbow trout and Pangasius fish appeared in two studies each. It was also found that some studies used Crayfish and Shrimp in their AP systems. The number for Carp was high because all types of carp, including Koi, were grouped together. The distribution of fish in studies could be due to ease of management. Tilapia for instance is a hardy fish and can tolerate a wide range of water quality conditions and densities whereas other aquatic species such as Crayfish and Shrimp are quite difficult to manage. Feed crude protein (CP) content ranged from 30% (*K*=1) to 48% (*K*=2). In one study, the CP was estimated as 84% from the description of feed given in that study. This might be a possible outlier for meta-regression between effect size and feed CP. Most of the studies used feed containing CP of 46% (*K*=6) followed by 32% and 38% with *K*=3 each. Fish stocking density ranged from 0.5 kg·m^{-3} (*K*=1) to about 53 kg·m^{-3} (*K*=1). A substantial number of studies did not report the stocking density (*K*=8). The predominant stocking density used was 7 kg·m^{-3} (*K*=3) followed closely by 6.4 kg·m^{-3} (*K*=3). Most of the studies used homogenous age composition (*K*=12) while 9 other studies used heterogeneous ages of their aquatic/fish species. One study did not report age composition of the aquatic/fish species. Assessment of aquaponics coupling type showed that almost all studies used coupled/single loop aquaponics system (*K*=20) whereas 1 study used decoupled system and 1 study did not indicate the type of coupling used.

Hydroponics systems were mainly Deep-Water Culture (DWC, *K*=9), media-based (*K*=6) and nutrient film technique (NFT, *K*=7). It should be noted that both organic and inorganic media were grouped as media-based system. Grow media used were light expanded clay aggregates (LECA, *K*=1) and perlite (*K*=3). Coconut coir, expanded vermiculite, and coconut shell fiber were grouped together as 'other' as shown in **Figure 1.5B** (*K*=3). Grow media used in studies that adopted DWC and NFT systems were grouped as none (*K*=15). This implied that more studies used DWC and NFT than all media-based systems combined. Distribution of crops showed that most of the trials were conducted using lettuce (*K*=10) as their test crop while a few studies used crops such as spinach, strawberry, tomato, basil, and cucumber. It was found that 13 out of the 22 studies examined did not supplement their aquaculture effluent.

1.1.3.2 Crop yield across studies

In order to understand crop yield across studies, there was the need to understand heterogeneity between studies. Heterogeneity between studies confound the pooling of data across studies into a common effect size. In our case, there was high between study heterogeneity which confounded the reliability of a common effect size or called for the need of subgroup analysis. Heterogeneity among the studies was assessed using the restricted maximum likelihood estimator (REML) and inconsistency index (I^2) (Higgins and Thompson, 2002). The authors classified I^2 -values into 0- 25%, 30-50% and ≥75% as small, moderate, and substantial heterogeneity respectively. The current review therefore revealed that substantial between study heterogeneity (I^2 = 100%; not shown) existed in the studies used for estimating the for overall effect size for AP and HP crop yield comparisons. Therefore, drawing conclusions on the overall effect size must be done with caution. This high heterogeneity could be due to high variability in aquaponics experiments. The slightest change in one component either from the aquaculture or hydroponic side can result in tremendous influence in heterogeneity. The results shown here (**Figure 2.1A**) are the overall effect size and the bootstrapped 95% confidence interval (CI).

When categorized based on study year, it was realized that effect sizes were variable for different study years. However, apart from studies in 2009 and 2017, all other study years seem to suggest that cHP crop performance is superior to AP performance (**Figure 2.1B**).

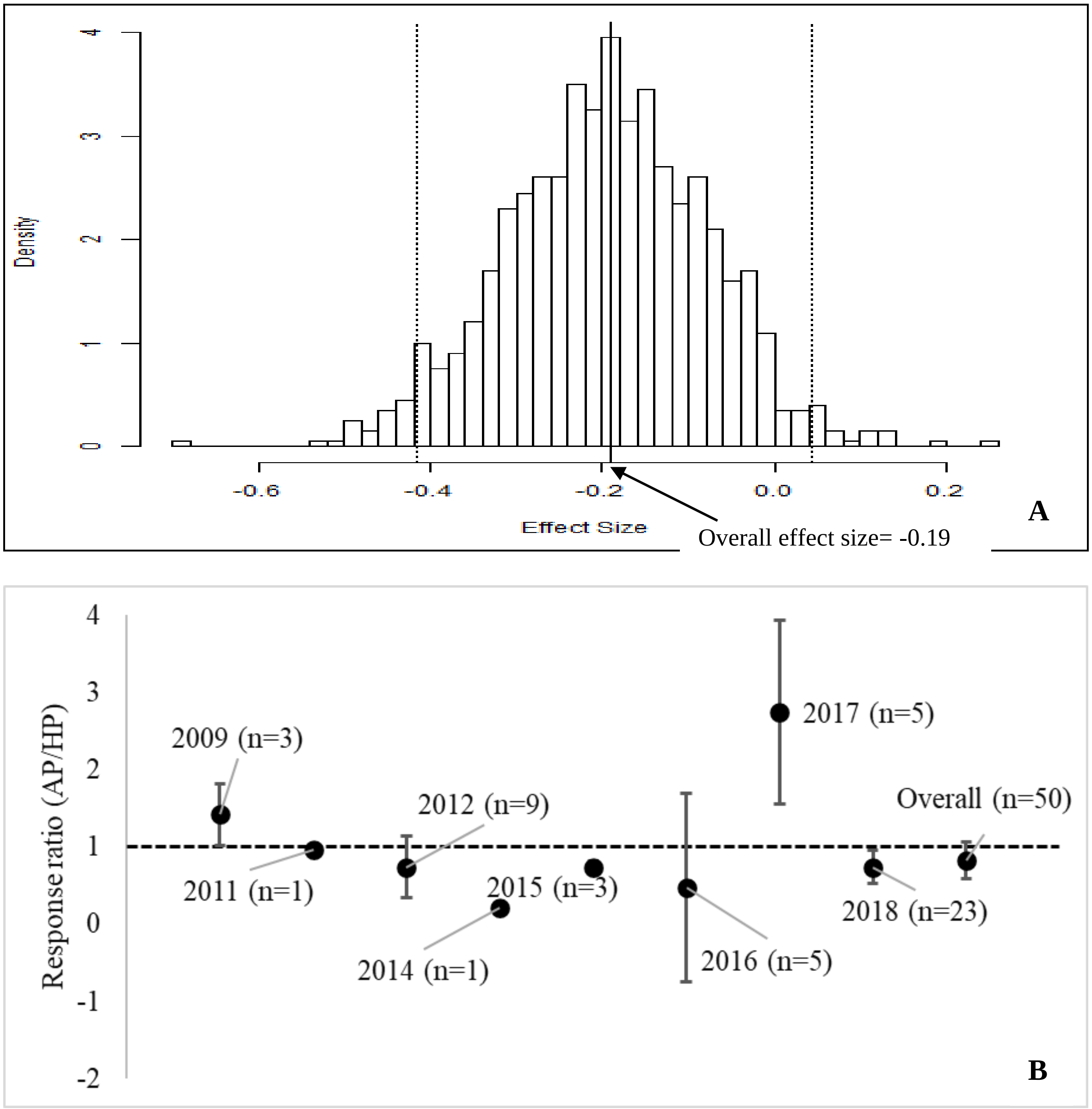


Figure 2.1. Bootstrapped histogram of overall effect size (middle thick line) and its confidence intervals (dotted vertical lines). Number of bootstraps = 1000, number of effect sizes for

resampling = 50, B) Effect size distribution over the period used in the meta-analysis; ‘n’ refers to number of effect sizes.

1.1.3.3 Publication Bias

Publication bias was assessed with Rosenthal’s fail-safe number and a funnel plot (**Figure 2.2**). The fail-safe number is an estimate of the number of non-significant studies required to nullify the results of the meta-analysis. A fail-safe number (FSN) greater than $5k + 10$ (where k is the number of studies) is enough to consider publication bias inconsequential (Rosenthal, 1979). That is, for our study, a fail-safe number greater than 120 would make publication bias inconsequential. A fail-safe number of 353 was obtained in the current study. Both the funnel plot and FSN were executed using the “metafor” package in R. The funnel plot was constructed with effect size (x-axis) against sample size (y-axis) because this study adopted an unweighted analysis approach.

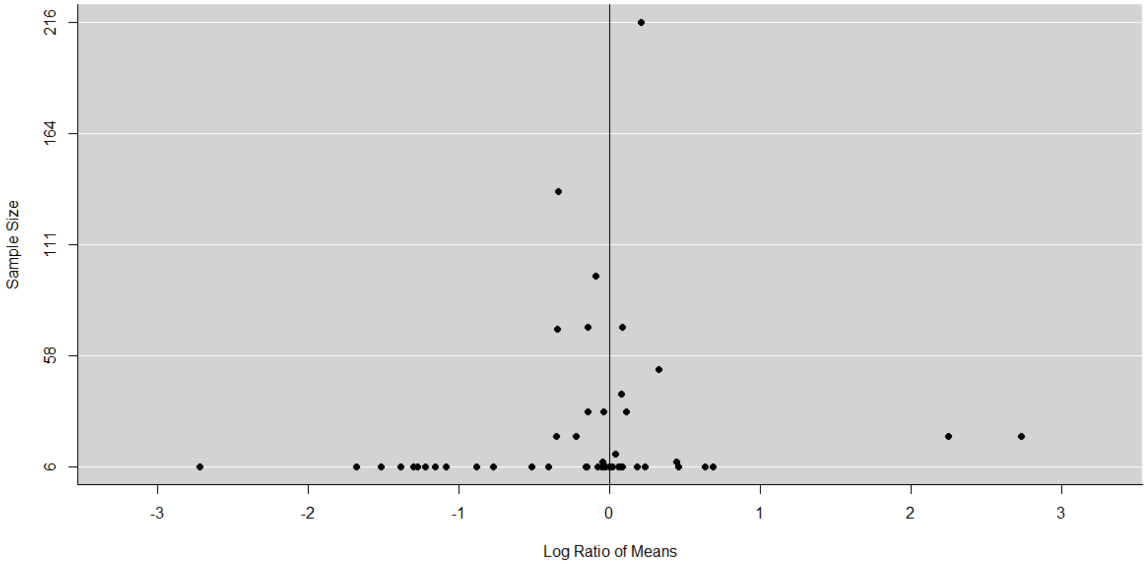


Figure 2.2 Funnel plot showing sample size distribution with respect to log response ratio**.**

1.1.3.4 Moderators

There was a significant effect of the moderators examined helping to account for the heterogeneity seen the results (**Figure 2.3**)

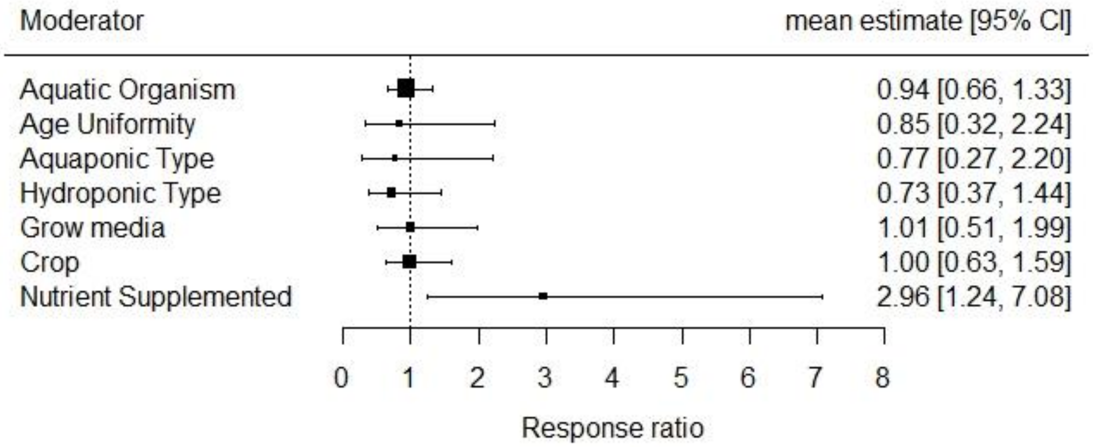


Figure 2.3. Effect of moderator on the response ratio (back transformed).

1.1.8 A. Hydroponic components

1.1.3.5 Hydroponic system and media type

Hydroponics system type accounted for 11.25% of the heterogeneity in crop yield among studies. Also, the extent to which AP crop yields compares with cHP yield was influenced by grow media. However, grow media accounted for only 0.44% of the heterogeneity among studies. When pooled, all media-based AP performed poorly (Figure 2.4**A**). However, a dichotomy of media type showed that organic media-based type performs better than other types of media (Figure 2.4**B**). The low performance of water-based system (labeled as none in Figure 2.4**B**) can be attributed to contribution from nutrient film technique (Figure 2.4**A**). Although some studies under deep water culture (DWC) fell below the null line (confidence interval extended beyond the null for DWC), most of the studies were beyond the null with an average positive effect size for DWC. This indicated that DWC systems generally resulted in better AP crop yield performance.

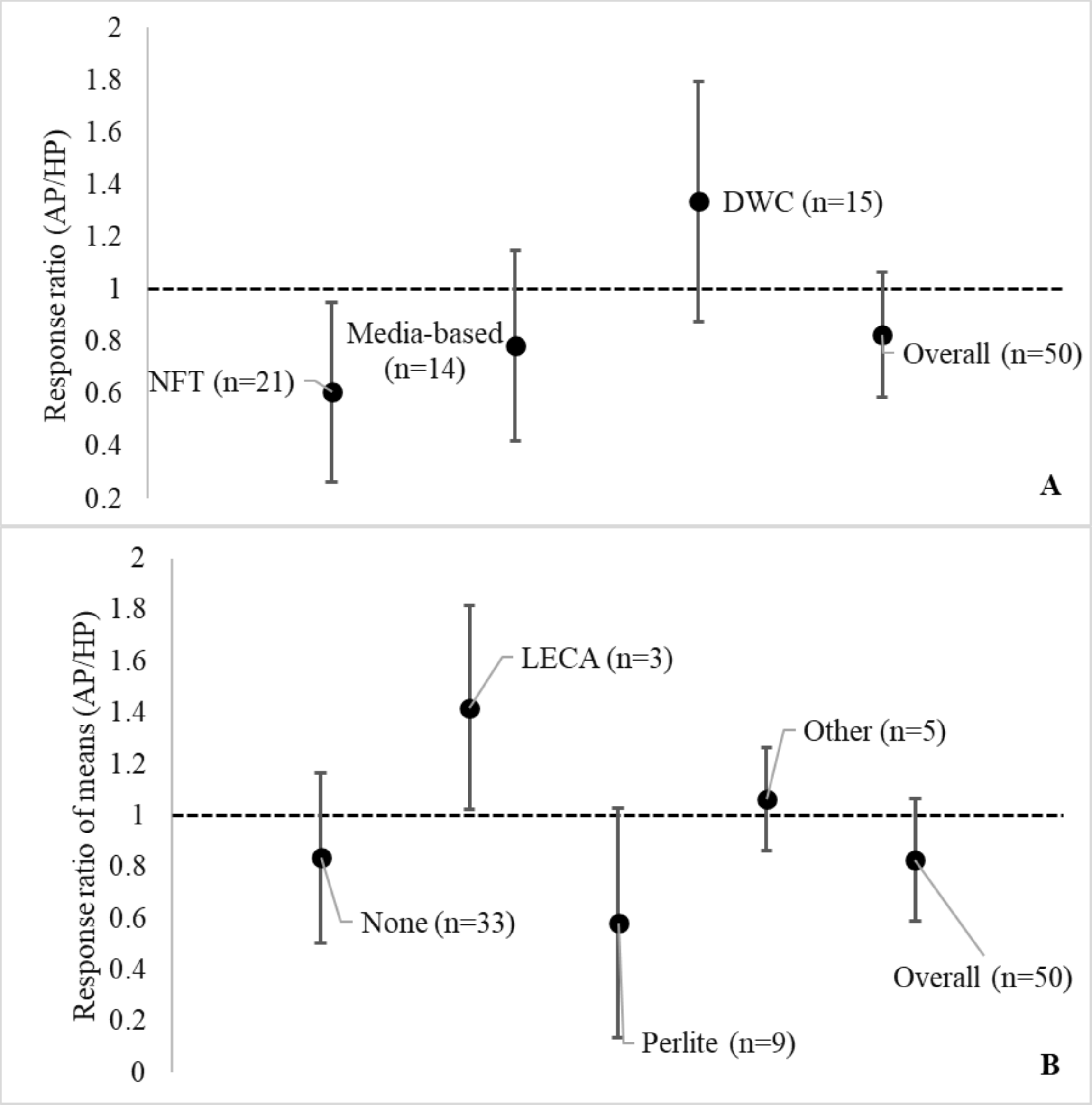


Figure 2.4. Effect of hydroponic system type (A) and grow media (B) on crop yield comparison between aquaponics (AP) and hydroponics (HP); ‘n’ refers to number of effect sizes. In A, ‘DWC’=Deep-Water Culture; ‘NFT’=Nutrient Film Technique. In B, ‘LECA’=light expanded clay aggregates. Full error bars are 95% confidence interval.

1.1.3.6 Crop species used

Generally, lettuce gave a better performance in AP systems than cHP systems compared to the other crops (Figure 2.5). Tomato (n=5), Aubergine (n=1) and Spinach (n=1) showed no difference between AP and cHP systems (Figure 2.5). However, these results are inconclusive due to fewer effect size(s) per crop. The case of Babyleaf too must be interpreted with caution because results came from the same study. That is, performance due to Babyleaf might be constrained by within study bias.

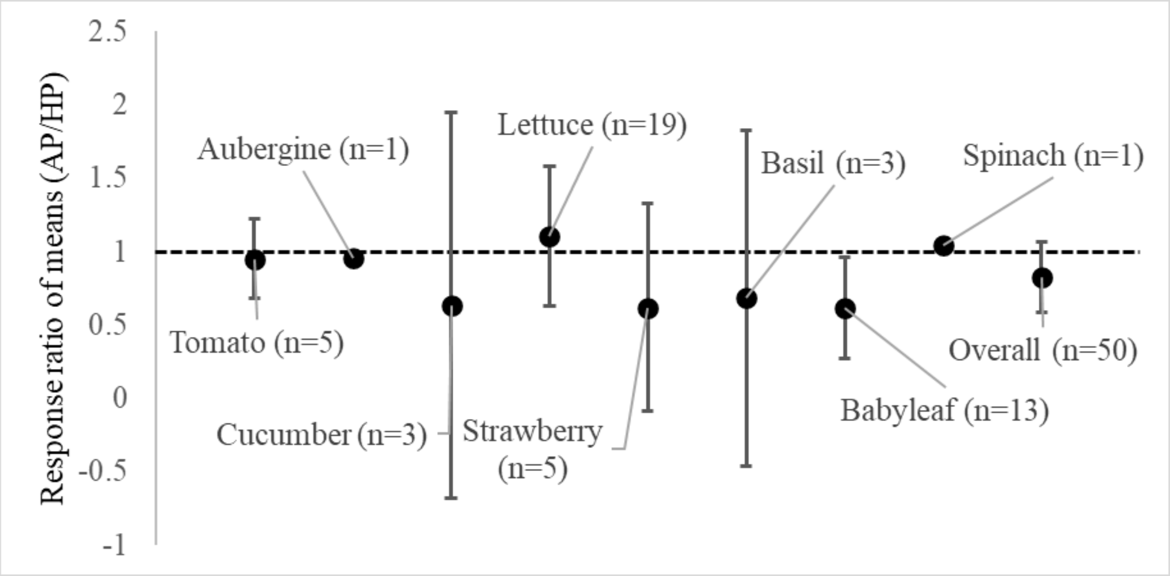


Figure 2.5. Differences in crop response to aquaponics (AP) and hydroponics (HP) nutrient sources. ‘n’ refers to number of effect sizes. Note that a study might have more than one effect size. Full error bars are 95% confidence interval.

1.1.10 A. Aquaculture component

1.1.3.7 Aquatic organism

A test of differences between aquatic organisms showed no significant difference between AP and cHP crop yield. However, this comparison was subject to substantial between study heterogeneity (I^2 >80%). Aquatic organism accounted for 43.9% of the heterogeneity in estimating the overall effect size. The results also showed that, effluent obtained from raising

Tilapia, Carp and Pangasius fish resulted in poorer relative crop yield between AP and cHP (Figure 2.6**A**). Here again, caution should be taken when interpreting the results of Pangasius fish because, results came from the same study. Results from Perch, Crayfish, Shrimp and Catfish are also inconclusive due to the limited number of studies involved in their estimation. Fish age composition influenced the crop yield performance between AP and cHP (Figure 2.6**B**). Generally, homogenous age composition resulted in lower relative crop yield between AP and cHP than heterogenous age composition. This might be because, most of the aquatic organism such as crayfish, shrimp, and catfish, which had higher effect sizes, fell into the heterogenous age category, thus skewing the results in favor of AP.

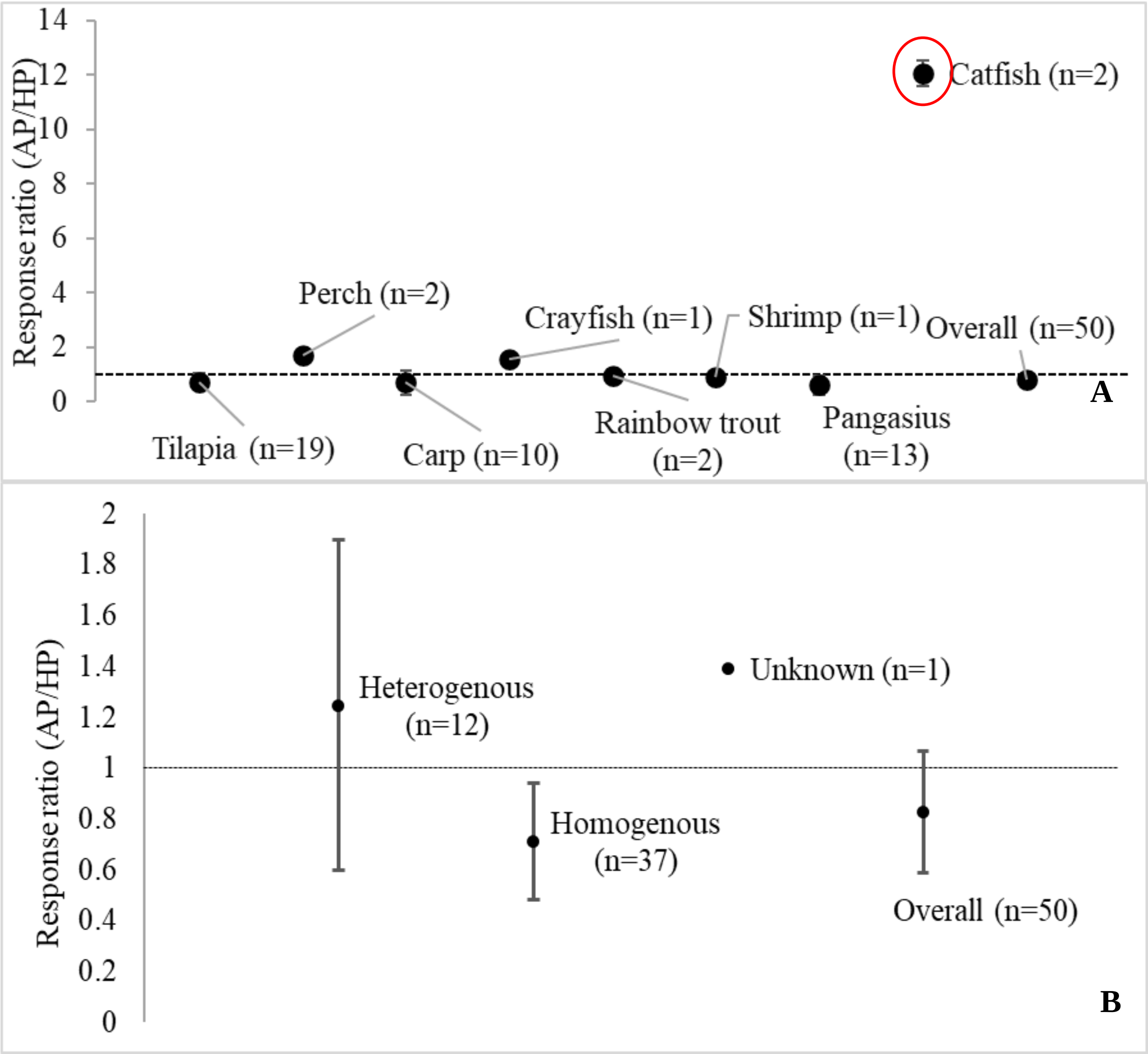


Figure 2.6. Effect of aquatic species (A) and age distribution (B) on comparative response of aquaponics (AP) and hydroponics (HP) crop yield. Full error bars are 95% confidence interval; ‘n’ refers to number of effect sizes.

1.1.3.8Type of aquaponics system

The results showed lower relative crop yields between AP and cHP irrespective of coupling (

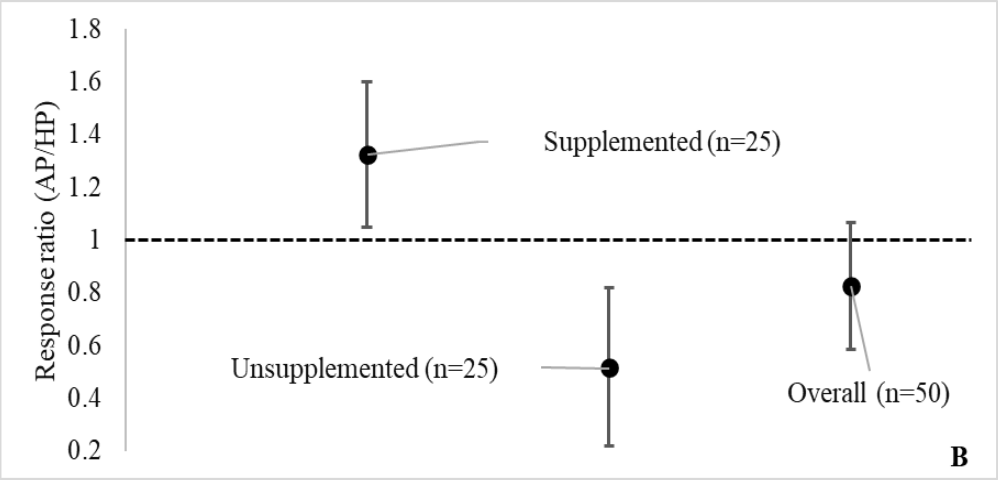


Figure 2.7**A).** Also, the decoupled system results came from one study and therefore should not be used as the sole basis to assess the performance of decoupled systems in general. This trend might change with more studies using the decoupled system. Generally, nutrient supplementation resulted in higher relative crop yield between AP and cHP (

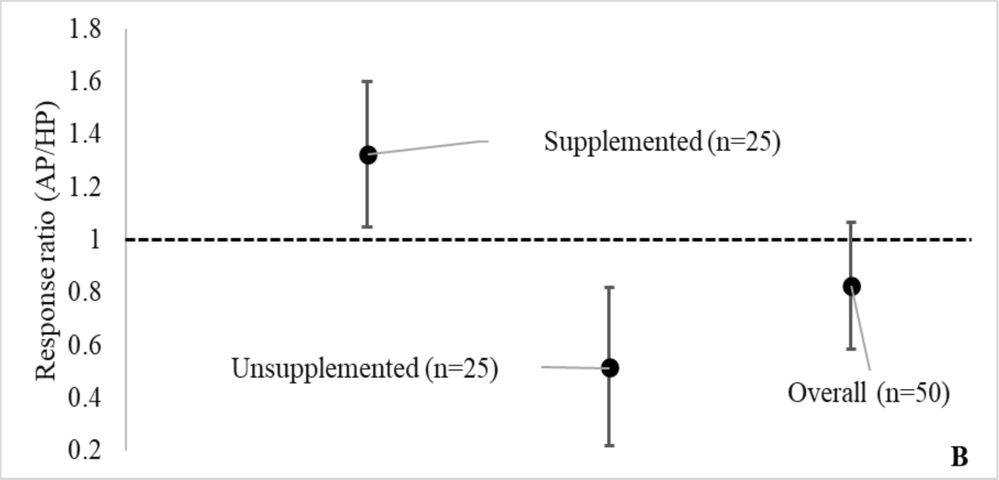
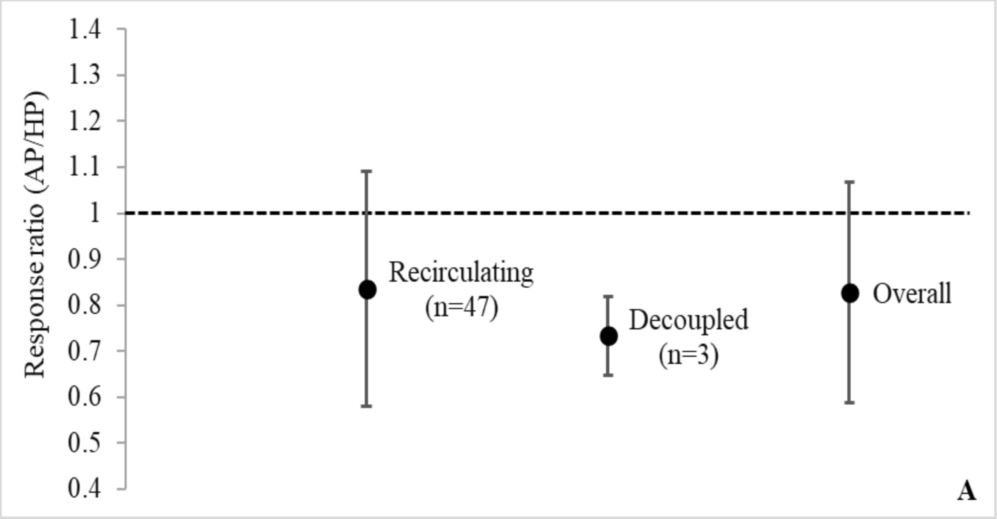


Figure 2.7**B**). However, studies that did not supplement with additional fertilizers achieved the opposite results. Nutrient supplementation accounted for 29.43% of the heterogeneity (results not shown).



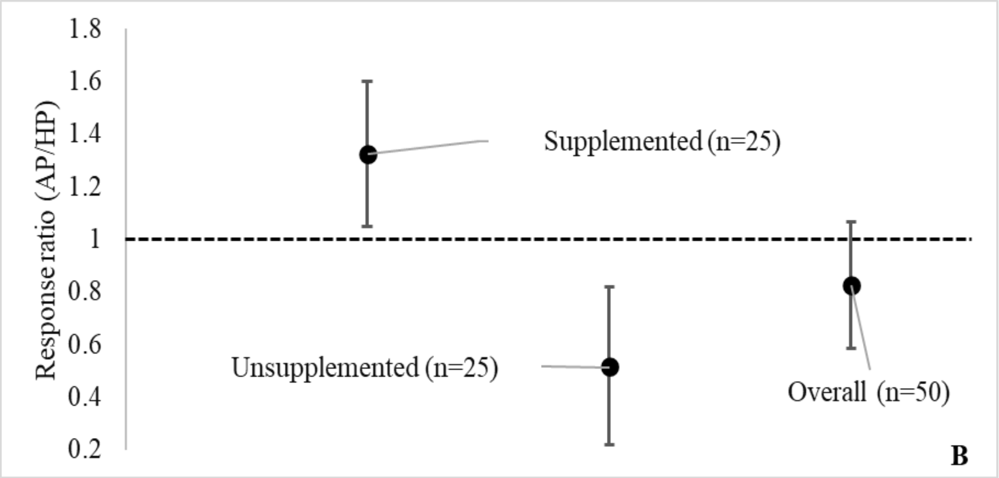
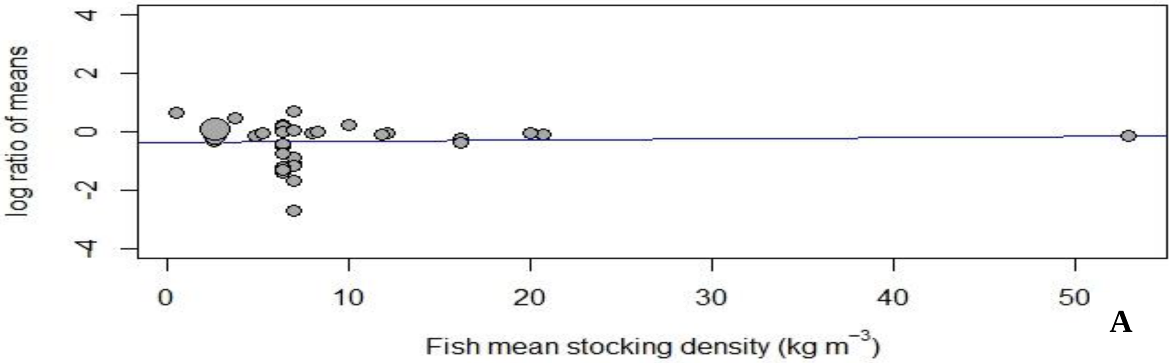


Figure 2.7. Effect of aquaponic coupling type (A) and nutrient supplementation (B) on crop yield comparison between aquaponics (AP) and hydroponics (HP). Full error bars are 95% CI; 'n' refers to number of effect sizes.

1.1.3.9 Stocking density and feed crude protein content

There was no significant relationship between mean stocking density or feed crude protein with effect size (Figure 2.8). There was an outlier with very high mean stocking density and crude protein. However, elimination of the outliers did not change the relationship (S§4). The results showed that increasing fish mean stocking density or increasing protein content did not result in increased AP crop yield.



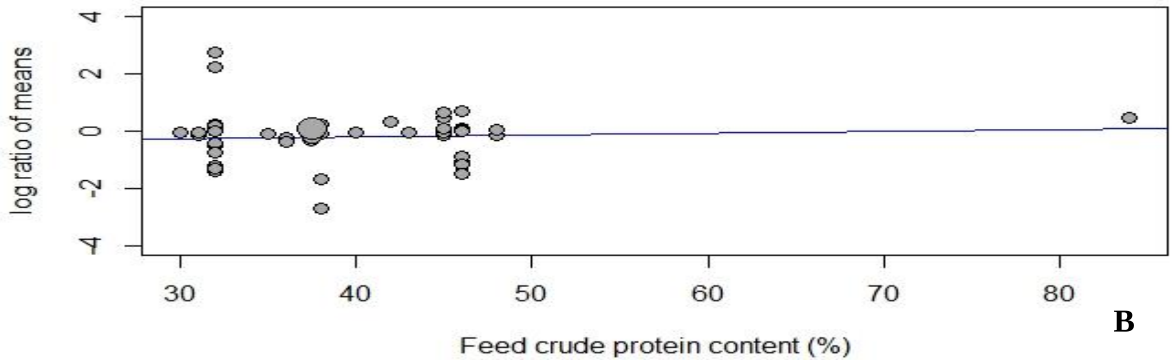


Figure 2.8. Meta-regression between A) fish mean stocking density and B) Feed crude protein content (%) with effect size.

Discussion

1.1.3.10 Crop yield across studies

Interest in aquaponics (AP) has grown over time. The interest to compare crop yields from AP with conventional hydroponics (cHP) increased from as low as 1 study in 2009 to as high 8 studies in 2018 (**Figure 2.1B**). This might be due to a realization that aquaponics has potential to contribute to food sustainability (Belsare et al., 2007; Kloas et al., 2015; Nehar, 2013; Price, 2009; Tyson et al., 2012). Most of the comparisons in the studies considered were done where cHP served as a control. However, in cases of nutrient supplementation trials, the main purposes were to examine how comparable AP crop yield was to cHP. The results showed that AP crop yields were generally lower than cHP systems even with nutrient supplementation. This was worse in studies that did not supplement. This was expected since fish effluent used in AP systems are usually low in crop nutrients especially micronutrients are non-existent (Bittsánszky et al., 2016). However, the overall crop yield obtained from AP showed no statistically significant difference from cHP. As stated above, this comparability was due to supplementation making their AP similar to cHPsystem. Nutrient supplementation is beneficial especially in the case of micronutrient where systems such as deep-water culture or nutrient film technique is used. However, this might also derail the sustainability goal of AP (Goddek et al., 2015). Alternative ways of enhancing AP crop productivity without nutrient supplementation such anaerobic digestion of sludge which returns nutrients lost through solid waste (Goddek et al., 2018), use of substrate-based systems which enhances microbial populations for improved nutrient uptake (Yi et al., 2018), and proper pH management (R. V. Tyson et al., 2008; R. V Tyson et al., 2008; Tyson et al., 2007) should be encouraged.

Although the meta-analysis indicate that AP crop yield is comparable crop yields with cHP, there was substantial between-study heterogeneity in estimating the overall effect size. Therefore, a subgroup analysis and meta-regression were explored further to understand contributing factors to this heterogeneity (Bown and Sutton, 2010). Substantial between study heterogeneity is characteristic of AP crop studies. This is because, no two AP systems are identical. Small modifications lead to substantial differences. Therefore, pooled comparison is not quite feasible although has been attempted in the current study. This attempt was to give a rough idea of the trend in how yields in AP compare with cHP.

In assessing the results of this meta-analysis, it was important to consider that publication bias could potentially detract from the outcome of the comparison. Although the fail-safe number of the analysis was estimated as being larger than the cutoff by Brown and Sutton (Bown and Sutton, 2010), this estimate was confounded by a lack sampling variance from the various studies to conduct a weighted meta-analysis. We are also aware that there might be studies which due to their non-significant p-values or other reasons might be rejected by Journal editors and that could not be accessed to be included in this meta-analysis and could influence publication bias. (Bown and Sutton, 2010). Since meta-analysis depends on findings of all studies, publication bias could affect interpretation of our results. However, we assessed the presence or absence of publication bias through funnel plot and fail-safe number. In our case, the funnel plot was based on the sample sizes rather than the standard error. Due to this we observed that the sample size distribution relative to effect size was not virtually symmetrical.

1.1.3.10 Subgroup analysis

The productivity of plants in AP depends highly on HP system type and plant grow media. Lettuce plants showed better productivity in a raft technology (DWC) than media (LECA) bed technology (Sirakov et al., 2017). This contrasted with another study which found that HP system type had no significant influence on tomato productivity (Schmautz et al., 2016). This contrast could be due to differences in species response to different grow media. The difference observed by (Sirakov et al., 2017) could also be due to the use of LECA which is has some cation exchange properties making it similar to organic material. Cation exchange capacity improves nutrient uptake of these organic based material. In another study, a combination of coconut fiber and crushed stones resulted in higher AP lettuce yield (Jordan et al., 2018). Thus, the need to explore more on AP crop productivity using different HP system types. Also, the reports show that a combination of various ratios of organic and inorganic grow media could be beneficial to improving AP crop yield (Roosta and Afsharipoor, 2012). In terms of HP system type however, DWC generally performed better than control. The interpretation of these results might change if nutrient supplementation is considered. Nevertheless, it can be assumed that since supplementation resulted in a positive impact on AP crop yield, this will positively influence the effect of grow media.

We found that, different crop species obtained different effect sizes. This implied that, relative crop yield between AP and cHP depended on crop. This information is important in the choice of crops to grow in AP. Our analysis showed that growing lettuce (*Lactuca sativa* L.) produced similar or better yields in AP relative to cHP than other crops (***Figure 2.5***).

Performance of lettuce could be because most of the studies that grew lettuce, grew them in deep water culture system and/or supplemented their nutrient AP nutrient source. The nutrient demand of crops such as tomato (*Solanum Lycopersicon* L.), cucumber (*Cucumis sativus* L.) and other fruity crops are higher than most AP system can supply making their yield incomparable with yields obtained from cHP systems. This is because nutrient uptake is strongly influenced by crop species (Buzby et al., 2016; Buzby and Lin, 2014).

*It was found that aquatic organism influenced the relative crop yield between AP and cHP (***Figure 2.6***). This is because aquaculture effluent nutrient quality is dependent on the aquatic organism used. In a gravel based ebb and flood coupled AP system, Knaus and Palm (U. Knaus and Palm, 2017) showed that fish species influenced crop species choice and yield. However, a different study that assessed the influence of 'Pacu' fish and Tilapia revealed no significant influence of the two fish species on crop yield of vegetable garnish (Pinho et al., 2018). Thus, no consensus on the conclusion of influence of aquatic organism on AP crop performance. In this study, aquatic organism accounted for 37% of the heterogeneity in the effect sizes obtained. This implied that aquatic organism contributed substantially to the variation in effect size for AP crop yield and should be considered an important factor in AP studies. Different fish species do not have the same influence on different crop species (U. Knaus and Palm, 2017). The subgroup analysis revealed that Tilapia and Carp have similar influence on crop yield comparison between AP and cHP (*

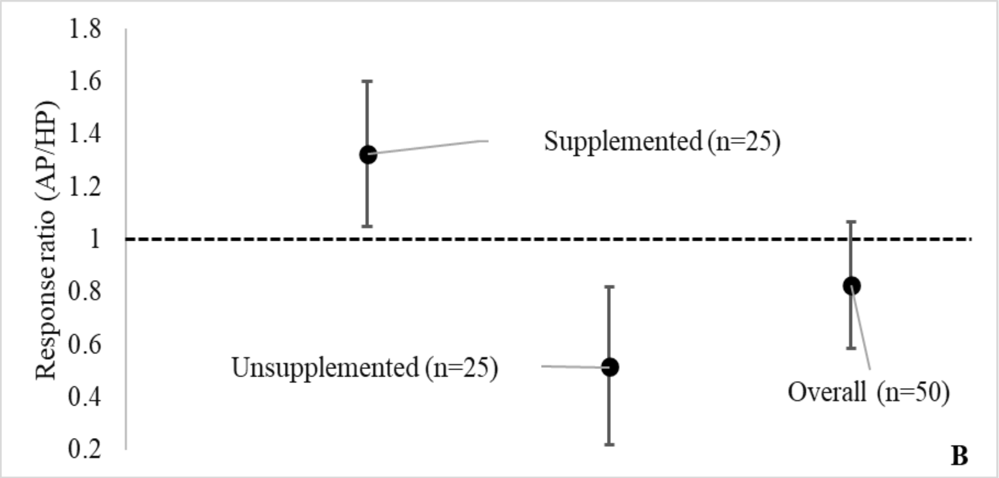


***Figure 2.7*A**). Other fish species had a potential for better AP crop yield than cHP system. However, there were too few studies to fully estimate their effect.

Currently, two types of coupling are known in AP; recirculating or single loop and decoupled or multiloop (Goddek et al., 2016). The current results showed that both coupling types resulted in lower AP crop yield relative to cHP (Figure 2.8**A**). However, the question of which coupling type gives better yield remains unanswered due to insufficient number of studies for decoupled AP. More studies that compare AP and cHP crop yields using decoupled systems would allow for a comprehensive conclusion on decoupled versus recirculating systems. However, although the type of coupling is important for adjustment of growth conditions (Goddek, 2017; Goddek et al., 2016), coupling type alone cannot lead to improved crop yields if the same growth conditions are achieved for both system types. That is, in a decoupled system, if growth conditions such as pH and plant nutrients are not adjusted, crop yield cannot be improved. This was the case of Pickens (Pickens, 2015) who found lower cucumber yields in a decoupled AP system compared with cHP fertilizer. Generally, low AP crop yield is attributed to low nutrient contents of aquaculture effluent. Rightly so, studies that supplemented their effluent solution with one or more nutrients achieved similar or higher AP crop yield than the cHP system (**Figure 2.3**). Nutrient supplementation of at least chelated iron is required in AP for the growth of healthy plant biomass (Buhmann et al., 2015)**.** Other studies achieved similar results when they supplemented their aquaculture effluent with required plants nutrients (Delaide et al., 2016; Goddek and Vermeulen, 2018). Therefore, in order to achieve comparable or better AP crop yields with cHP nutrient supplementation is an important consideration.

1.1.15 Conclusion

AP is a new field of farming which has attracted keen research interest. Comparison of AP and cHP in terms of crop yield is a recent topic of interest with studies dating not more than a decade in this meta-analysis. The meta-analysis showed that overall crop yield obtained from AP was not statistically significantly different from cHP. However, contribution of nutrient supplementation to this non-significant effect is high. More than half of between-study heterogeneity was explicable by aquatic/fish species used and nutrient supplementation. Nutrient supplementation resulted in similar or even higher AP crop yield than cHP. Important factors that accounted for crop yield differences between AP and cHP were aquatic/fish species, hydroponic system type, type of grow media, and crop species on aquaponics crop yield. Coupled and decoupled AP both had lower relative aquaponics crop yield. Generally, the study showed that to have a better or comparable AP with cHP crop yield, lettuce is a better choice, floating raft (DWC) should be used and if media-based then organic media would be better, best aquatic organism would be Tilapia, and need to supplement your aquaculture effluent with at least iron.

Challenges of this study and Recommendations

The main challenge of this meta-analysis was that most authors failed to report the variance around their means. This resulted in the choice of unweighted over weighted meta-analysis. Weighted meta-analysis would have been more robust than unweighted. Since unweighted meta-analysis assumes similar contributions from studies, the overall outcome is not a true reflection of variability among the studies. It is recommended that journal editors should strongly encourage the reporting of standard deviation, standard errors, or confidence intervals of means for these types of studies. This will enable an all-inclusive future meta-analysis. Also, lead authors should be transparent and kind enough to give out information about the studies when contacted.

The limited number of studies of most of the factors examined reduced the rigor of subgroup analysis. Therefore, there is the need for future studies to focus on comparison of decoupled systems output with conventional hydroponics to give credence for future subgroup analysis. Also, other aquatic/fish species should be explored to assess their potential to improve aquaponics crop yield over conventional hydroponics.

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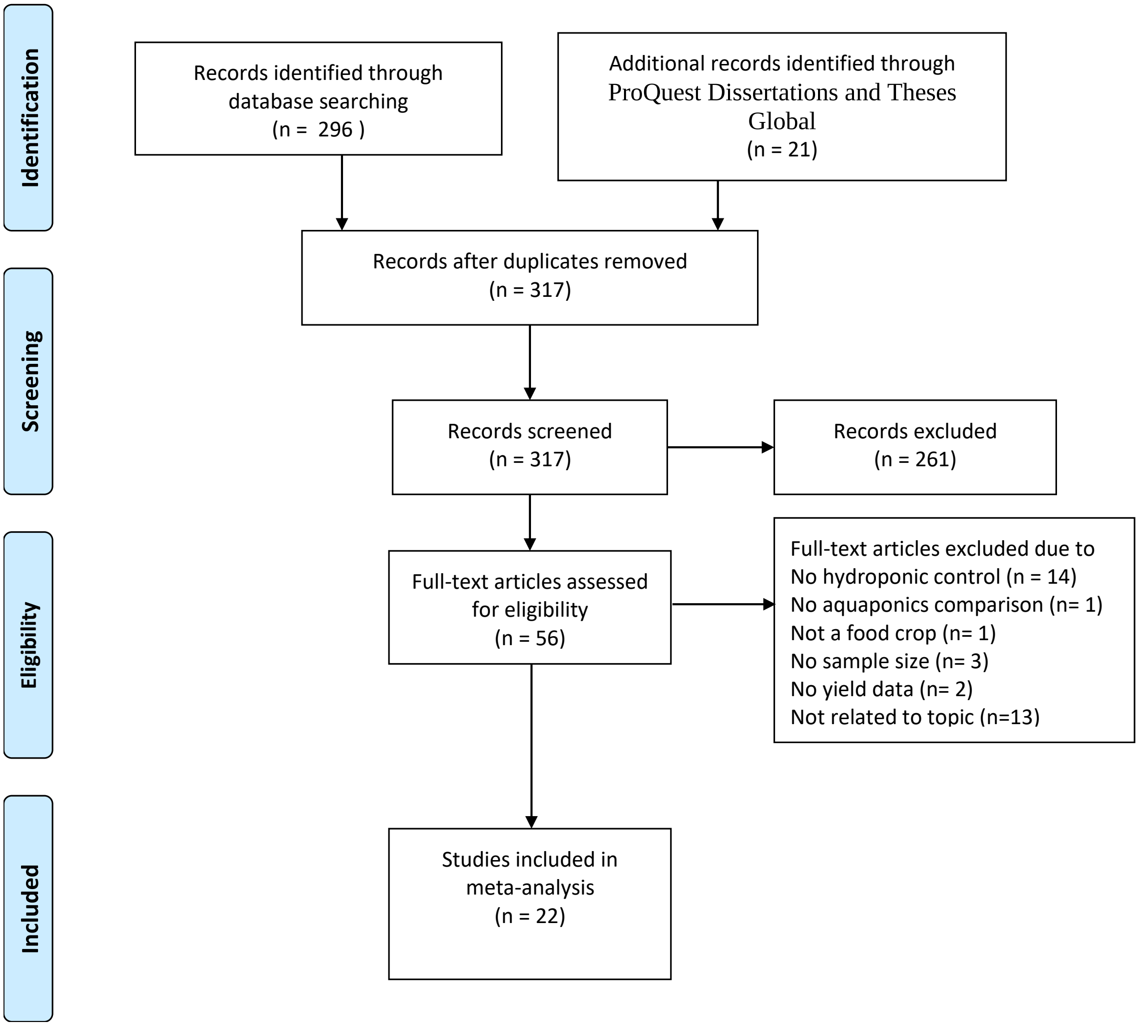
Conflict of Interest: The authors declare no conflict of interest.

Supplementary materials

S§1: PRISMA flow chart



PRISMA Flow chart adopted from Moher et al. (Moher et al., 2009)

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2.2 Review of irrigation and fertigation approaches of greenhouse cucumber

2.2.1 Deficit irrigation and partial root zone drying

Deficit irrigation and partial root zone drying have been tested as irrigation management approach in soilless greenhouse cucumber production combined with open and close system. That is with or without water re-use, it was found that recycling saved up to 46.7% nutrient solution in the control (fully watered) combined with closed system treatment compared to the open alternative (Dasgan, et al., 2012). The study indicates, water savings with closed systems is at variance with increased cucumber yields. Therefore, although water is saved in recycling water, yield is penalized at its expense. Improving water use of cucumber has also be achieved through addition of zeolite and hydrogel. It was found that addition of 2% zeolite + hydrogel improved physicochemical properties of substrates and enhanced water retention capacity, and leads to increases in cucumber yield especially when combined with partial root drying rather than deficit irrigation (Gholamhoseini et al., 2018). Use of zeolite to enhance water and nutrient availability is a potential research area that can be explored in aquaponics with consideration made to environmental footprint.

2.2.3 Irrigation based on evapotranspiration

Optimum water amounts are required to improve irrigation water use efficiencies (IWUE) and irrigation water saving. Therefore, Abdalhi et al. (2015) recommended that for greenhouse soil-grown cucumber, 100% crop evapotranspitration rated within the greenhouse (ETc,in) for increased yields in cucumber although irrigating at 50% ETc,in resulted in the highest water saving of 102.9 mm and irrigation water use efficiency of about 0.340 t ha $^{-1}$ mm $^{-1}$. The ETc based irrigation seem very unresolved and different studies offer different recommendations. For instance, Rahil and Qanadillo (2015) examined the effects of different irrigation regimes on yield and water use efficiency of cucumber crop. They showed that, 70% ETc treatment obtained the highest crop yield of 59.52 t ha^{-1}, 70% ETc- and tensiometer-based irrigations had similar water use efficiency of about 31 kg m^{-3}, and plant dry matter obtained under 70% ETc treatment was higher than the other treatments. Ultimately, it was recommended that irrigating at 70% ETc results higher cucumber yield. Their results contrasted the results of Dasgan et al. (2012) who found 100% ETc to be the ideal irrigation regime for increased cucumber yields. Additionally, Rahil and Qanadillo (2015) found that tensiometer-based irrigation resulted in the highest amount of water saved (139 mm). Alsaeedi et al. (2019) showed that improvement could be achieved with ETc-based irrigation by combining it with amorphous silica nanoparticles (SiNPs) to enhance growth and yield of cucumber under water deficit and salinity stresses. Their results showed that applying SiNPs at rate of 200 mg kg^{-1} increased cucumber yields receiving 85% of their ETc-based irrigation with corresponding increase uptake of nitrogen by 30%, potassium by 52, 75 and 41% in root, stem, and leaf, respectively. What is more, studies in China indicated that irrigating at 75% ETc is possible (Wang et al., 2019a). Wang and colleagues assessed how cucumber water and nitrogen (N) requirement was influenced by a newly developed fertigation in a shallow groundwater region in China. They found that irrigating more frequently (every 2 days irrigation interval) combined with 75% of estimated plant evapotranspiration (0.75 ETc) was optimal to obtain the highest yield, IWUE and WUE in the study area. However, reducing ETc down to 50% hampers N uptake (Wang et al., 2019a). Reference evapotranspiration (ET_0) is similar to the ETc except that ET_0 does not include the crop coefficient. However, there have been irrigation scheduling approaches based solely on ET_0. In the study of Wang et al. (2019b), the response of cucumber yield, fruit quality, and water and nitrogen use efficiency to irrigation level was based solely on ET_0 and nitrogen fertilization. Their results showed that, the highest water use efficiency (WUE) of 55.8 kg m^{-3} was obtained from conditions involving medium irrigation levels of 80% ET_0 and an application of 360 kg ha^{-1} N. Yet, the highest soluble sugar content of 2.8% was achieved at irrigation level of 60% ET_0 (the lowest irrigation amount) with same N rate as above. Therefore, under those conditions, a combination of 80% ET_0 irrigation with 360 kg N ha^{-1} was the best fertigation strategy.

2.2.4 Irrigation based on Pan evaporation

Pan evaporation is another way of quantifying water loss in the environments. The idea simulates a body of water that is being exposed to evaporative forces. It is assumed that the plant water loss behaves in similar fashion thereby, supplying the plant with similar quantities of water loss by the pan would meet the crop water requirements. It is a similar concept as the ET_0. In a study to identify the most appropriate irrigation application and water use efficiency for mini (Lebanese) type cucumber plants grown as a first crop under protected conditions in a solar greenhouse, Çakir et al. (2017) developed their program based on a Class A Pan evaporation. They found that cucumber yields increased with increases in irrigation water amount achieved at the highest crop Pan coefficients of 1.50. However, their study showed that the best IWUE and WUE is obtainable at crop Pan coefficient of 0.75, but this resulted in the lowest yields for cucumber. This result underscores the difficulty in increasing water use efficiency whilst maintaining optimum crop yields. Therefore, the study by Tüzel et al. (2017) was well-placed. A comparison was made between the performance of a low cost, short-range, wireless soil moisture sensor with Class-A pan evaporation method for irrigation in cucumber**.** It was revealed that the sensor-based irrigation can lead to both increased yields and water use efficiency. Their finding is a positive contrast to the previous literature on irrigation scheduling where yield is always compromised in treatments that increased water use efficiency. More research needs to be conducted in testing such approaches in different conditions for wide adaptability.

2.2.5 Irrigation based on solar radiation

Solar radiation is the driver of assimilate production, growth as well as transpiration. Therefore, irrigation scheduling based on solar radiation is a usual approach to meeting the crop water requirements. This approach was used by Duman et al. (2017) to investigate if integrated solar radiation programmed irrigation has effect on biomass, yield and water use efficiency of cucumber grafted on different commercial rootstocks. Their results showed that, irrigation program based on indoor integrated solar radiation level of 2 MJ m^{-2} is sufficient for grated cucumber especially in three of their rootstocks used. In a similar study, Truffault et al. (2017) compared irrigation based on solar radiation with irrigation based on leaf to air vapor pressure deficit ($VPD_{leaf\text{-}air}$) approach. They found a higher correlation between plant water consumption and solar radiation. However, they could not accurately determine a $VPD_{leaf\text{-}air}$ threshold. Also,

$VPD_{leaf\text{-}air}$ could not be applied for irrigation scheduling from the second period of the second crop to the final period of cucumber crops. They authors admitted that irrigation management based on VPDleaf-air does not consider the real transpiration of the canopy and therefore was not accurate to scheduling irrigation. Hence, solar radiation-based irrigation was still considered better than vapor pressure deficit approach.

2.2.6 Irrigation based on soil water potential

Buttaro et al. (2015) investigated irrigation management of greenhouse tomato and cucumber using tensiometeric approach. They showed that 46% water was saved when irrigation was done at -300 hPa and resulted in 8% higher dry matter than irrigating at -100 hPa. Seasonal effect on cucumber response to the irrigation treatments was not observed. Irrigating at -300 hPa could lead up to 49% water saving in cucumber production. This was the only study reviewed that used water potential approach. The approach is quite simple and amenable to both soil-and soilless-based systems. This approach can be combined with other methods to optimize irrigation water management. Therefore, there is a need to explore the method further, especially examining its suitability under different substrate types.

2.2.7 Irrigation based on simulation models

Models are very important decision support tools and their use vary depending on practicability and/or sophistication. As irrigation scheduling is a huge challenge which requires a combination of so many factors to optimize, simulation models might come in handy. This review found two studies that used models directly related to irrigation/fertigation scheduling. One of such approaches was by Sun et al. (2019) who calibrated and validated the EU-Rotate_N model and used it to identify the best management practice of water and N fertilizer for greenhouse summer cucumber in North China. This model was previously developed for use in southern European conditions and for estimation of nitrogen movement in the soil through leaching due to management practices. They calibrated and validated the model with data from four different water and N fertilizer treatments. They found that maximum cucumber yield was obtainable at water input of about 277 mm and that nitrogen started to lose as nitrate leaching when irrigation was increased to 300–400 mm. After 300 mm of irrigation, they realize nitrate leaching increased with every increase in irrigation. Cucumber yield increased to maximum values as N fertilizer input reached to about 313 and 310 kg N ha^{-1} for furrow and drip irrigation, respectively. Yield-irrigation relationship was a positive linear plateau which either increases linearly with every increase in irrigation when water input is about 277 mm or remains unchanged when input exceeds 277 mm. Thus, the best management practice under furrow irrigation condition were to irrigate 300 mm with 300 kg N ha^{-1} and 250 mm with 300 kg N ha^{-1} under drip irrigation condition for greenhouse cucumber in the study area. Another model applied was a Shuttleworth-Wallace model by a group of scientists also from China to estimate the evapotranspiration for cucumber plants based on in a Venlo-type greenhouse (Huang et al., 2020). They found that, leaf area index (LAI) reached a maximum of 4.67 around day 50 from transplanting and values of aerodynamic resistances in the greenhouse were quite higher than the results in the open field. They argued that the parameterized model is reliable in simulating the crop evapotranspiration (ETc) and Transpiration (Tr) in the greenhouse and recommend that the model could be useful in ETc/Tr based irrigation scheduling approaches. In this review, it is argued that the use of the model might be limited due to heavy measurement sensors and parameterization required.

2.2.8 Fertigation

Fertigation is used where the fertilizer is supplied in the irrigation water. Irrigation scheduling under such conditions is quite different since an adjustment in the amount of water also affects the amount of nutrients supplied. Fertigation is similar to challenges encountered when fertigating with aquaculture effluent where irrigation scheduling must meet both water and nutrient requirements of the crop. A study by Singh et al. (2018) showed that fertigating at 100% when combined with a cucumber variety called Multistar resulted in the highest fruit yield (3.4 kg plant^{-1}) and WUE (128.6 kg m^{-3}). However, 70% fertigation combined with the same variety resulted in the highest nitrogen use efficiency. The study of Singh et al. (2018) was the first study the review found to adopt a fertigation regime similar to fertigating with aquaculture effluent where the amount of water supplied directly affects the amount of nutrients as well. However, the authors did not indicate which of the irrigation approaches discussed above they based their 100% fertigation scheduling i.e, whether ETc, container/field capacity, $ET_{0,}$ or tensiometer. Nevertheless, fertigation amount was increased based on different growth stages of the plant, and results showed different water consumption patterns for different seasons.

2.2.9 Other irrigation approaches in cucumber

Improvements of irrigation with saline water have been tried by Cao et al (2016) to attenuate the negative effects of irrigation with saline water on cucumber (*Cucumis sativus* L.) by using a straw biological-reactor (SBR). Their results showed that under saline water irrigation conditions, soils treated with SBR showed significantly lower salinity, Na^+ concentration and pH in the main root zone of cucumber, and significantly higher plant biomass and cucumber fruit yield, when compared to untreated soils. Saline water irrigation decreased total soluble sugars, titratable acidity, and vitamin C in cucumber fruit. They found that the negative effects of saline water on fruit quality were significantly reduced by SBR application. However, SBR was not effective in reducing Na^+ accumulation in shoots or roots nor was it effective in enhancing K^+ accumulation (which are related to reduction in transpiration rates) but the presence of SBR enhanced shoot, root, and fruit biomass over the others. Ultimately, application of SBR would not be effective in increasing crop WUE but this was not measured in their study. Although this study does not directly relate to irrigation scheduling, it underscores the need to examine ways to ameliorate challenges of poor water quality in irrigation. Also, the use of aquaculture effluent from brackish water could be explored using this approach.

2.2.10 Discussion

The literature shows that irrigation scheduling still trends in greenhouse cucumber production with as recent as the year of this review (2020) to find efficient way of meeting the crop water and/or nutrient demands. Varying levels of sophistication exits based on data requirements which informs what and how many sensors/devices to use (**Table 2.1**). There were more soil-based studies constituting 68.8% of the studies reviewed than substrate-based studies. Focus on soil-based studies might be due to perceived difficulty in controlling irrigation in soil-based systems due to leaching, and/or deep percolation. Unlike substrate-based cultures where water lost via leaching could be captured and recirculated, in soil-based systems, water lost via leaching or deep percolation is not recoverable.

Table 2.1. Summary of data and sensors/devices requirements based on various greenhouse cucumber irrigation approaches.

Irrigation approach	**Data required**	**Sensors/devices required**	**reference**
ETc/ET_0[z]	Minimum and maximum air temperatures, relative humidity, wind speed, sunshine hours, solar radiation, Soil heat flux	Weather station inside and/or outside the greenhouse; soil temperature sensors	Abdalhi et al. 2015; Alsaeedi et al. 2019; Rahil and Qanadillo, 2015
Pan Evaporation	Pan coefficients, leachate volume, irrigation water volume	Class A Pan, lysimeter, water meter	Çakir et al. 2017; Tuzel et al. 2017
Solar radiation sum	Radiation	Pyranometer	Duman et al. 2017

[z] Crop evapotranspiration (Etc), reference evapotranspiration (ET_0).

Table 2.1 Continued

Irrigation approach	Data required	Sensors/devices required	reference
Field/container capacity	volumetric soil or substrate water content, bulk density	Sensitive weighing scale	Gholamhoseini et al. 2018; Dasgan, Kusvuran, and Kirda 2012; Singh et al. 2018
Tensiometric	soil water potential	Tensiometer	Buttaro et al. 2015; Rahil and Qanadillo, 2015
Model based	Various soil and weather	Weather station and/or soil sensors	Sun et al. 2019; Huang et al. 2020
Vapor Pressure deficit	leaf and air temperatures, Relative humidity	Laser Thermometer, air temperature sensor, RH sensor	Truffault et al. 2017

In terms of traits of interest, the goal of many of the studies reviewed here was to improve irrigation (IWUE) and/or crop water use efficiency (WUE). This is probably one of the most important assessment characteristics of productivity in irrigation scheduling. It tells the gains per unit supply of resource, in this case, water, or nutrient. Yet, optimal values of IWUE and WUE have not been established in cucumber production. There is need to standardize such a measure for easy comparison of research findings. Studies from China tops the list with 37.5%

followed by Turkey (25%), probably due to water scarcity in these areas. However, water scarcity has not always been the only reason for optimum irrigation scheduling as exemplified by Wang et al. (2019b) where groundwater was shallow with need for proper water management to minimize contamination thereof.

Irrigation scheduling based on either crop evapotranspiration rate (ETc) or reference evapotranspiration rate (ET_0) together with Pan evaporation, and irrigation based on solar radiation are similar in nature. Truffault et al. (2017) argue that, using solar radiation alone is not sufficient for optimum irrigation scheduling because, it does not consider feedback from the crop. Each of the methods mentioned above intends to replace the water lost by the plants by supplying the exact water due to evaporation and/or transpiration or a reduced amount. These approaches require accurate estimation of the ETc, ET_0 or Pan evaporation rates. The values are affected by different growing conditions, hence the disparity in results obtained in the literature for similar approaches.

In soilless culture alone, irrigation response is affected by type of substrate due to different levels of porosity and thus water holding capacity. In very porous substrates such as perlite, less water is absorbed by the plants whiles most of it is drained out which requires increasing irrigation frequency and reducing amount to reduce drainage to acceptable limits. Roh and Lee (1996) found increased drainage rate of perlite grown cucumber even when solar radiation was used to schedule irrigation. Other studies also found that shorter duration irrigation intervals were better at saving water and increase cucumber yields than the longer duration intervals (Mannini, 1988; Wang et al. 2019a). Therefore, it is not just enough to supply the ETc needs of the plants but how the amount of water is distributed greatly affects the drainage fraction, and yield. Studies are therefore needed which focus not just on amount but distribution of amount. This call is even more important in fertigation because water amount affects nutrient amount. Optimizing fertigation distribution will be helpful in reducing drainage fraction and prevent leaching because open drainage fraction affects nutrient and water use efficiency (Dasgan et al., 2012) as well as poses environmental concerns. To optimize resource use in the system, simulation models could serve as good decision support tools. However, models such as the EU rotate N (Sun et al., 2019) or the Shuttleworth-Wallace (Huang et al., 2020) are not very user friendly and require extensive parameter estimation. Modeling approaches that consider the physical and chemical properties of the substrate, the grow environment and plant characteristic would be easy for adoption under other conditions.

2.2.11 Conclusion

Choice of greenhouse irrigation scheduling approach suitable for de-couple aquaponics from the methods reviewed seems quite challenging due to the surprisingly high number of soil-based irrigation trials. However, fertigation methods seem the most plausible choice as they mimic the aquaponics problems. A combination of approaches might be required to fully understand and manage irrigation/fertigation in de-couple aquaponics systems. Due to the limited number of studies on timed irrigation, there is need to consider how timed irrigation could be used to manage irrigation frequency and duration for optimal water and nutrients use in de-couple aquaponics system.

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Chapter III

3.0 Performance of Greenhouse-Grown Beit Alpha cucumber in Pine Bark and Perlite Substrates Fertigated with Biofloc Aquaculture Effluent

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Abstract

Using aquaculture effluent (AE) to fertigate plants is gaining popularity worldwide. However, in substrate-based systems, choice of substrate is essential due to their effects on crop productivity. Differences in nutrients retention by substrates makes it necessary to assess suitability for use in AE. This study was conducted from January to July in 2016 and September to October in 2019 to evaluate greenhouse-grown Beit Alpha cucumber (*Cucumis sativus* L. ’Socrates’) performance fertigated with AE in pine bark or perlite substrates, grown either as one plant or two plants per pot. A 2 x 2 factorial arrangement in a randomized complete block design with four replications for each season was used. Substrate effect on yield in 2016 depended on density and season. Pooled yield over seasons in 2016 showed pine bark had significantly higher yield than perlite by 11% in one plant per pot but lowered by the same amount in two plants per pot. In 2019, pine bark significantly reduced leachate pH in both plant densities, and reduced leachate EC by about

15% in two plants per pot. Foliar boron was occasionally below sufficiency whiles manganese was above sufficiency in pine bark due to its inherently low pH. We conclude that effect of the substrates on cucumber yield fertigated with AE is dependent on season and number of plants per pot. Therefore, due to the local availability of pine bark, it could be a potential substitute forperlite especially when using one plant per pot for AE. Also, pine bark could be used as an intermediate substrate to reduce pH in AE for downstream use.

Keywords: Aquaponics, soilless cucumber, Leachate pH, cucumber yield

3.1 Introduction

The use of aquaculture effluent (AE) as a nutrient source for plant production is gaining popularity worldwide with exponential growth from 2004 to 2012 (Love et al., 2014). Aquaponics is a term used to describe a plant production technique in which at least 50% of plant essential nutrients are obtained from an aquaculture systems (RAS) (Palm et al., 2018) and can be coupled with different hydroponic systems. Biofloc technology is used to distinguish RAS technique in which biofiltration, i.e conversion of total ammonium nitrogen into nitrates by nitrifying bacteria, and aquaculture co-habit in the same unit. Therefore, biofloc technology is different from typical RAS or “clear water” systems in which biofiltration is separated from the aquaculture unit. The biofloc technology shows promising benefits for crop productivity with better growth and quality in lettuce (Pinho et al., 2017).

Substrates differ greatly in their physical and chemical properties leading to differential effects on plant productivity. Substrates of inorganic or mineral origin such as perlite predominate in hydroponics systems due to their consistent composition and predictable performance. However, perlite substrates tend to have neutral or near neutral pH which may not be a good combination with the already high pH of AE. Aged and/or composted pine bark is an organic substrate that has been used predominantly in containerized ornamental production (Papadopoulos, Athanasios P. Asher et al., 2008). However, pine bark substrate has higher air-filled porosity resulting in lower water holding capacity than perlite (Shaw et al., 2004). In a pour through experiment, pine bark substrate had less available water and retained less nitrogen i.e.NO_3^--N and NH_4^+-N, implying more N would be drained out (Jahromi et al., 2020; Niemiera et al., 1994) when used. Although perlite is also porous, due to its smaller particle size, it has higher plant available water (Grillas et al., 2001). On the other hand, pine bark substrate has low pH (Shaw et al., 2004) which may offer a better combination with AE than perlite.

Assessment of substrate effect shows that cucumber marketable yield, fruit count and plant height were highest in peat substrate which had significantly higher water holding capacity, cation exchange capacity and organic matter content than perlite and other substrates with lower water holding capacity (Peyvast et al., 2010). However, in the same study when perlite, was compared with bark mixed with peat of 50% v/v resulted in similar performance of the cucumber crop (Peyvast et al., 2010). Pine bark and perlite substrates also had similar effects on beit alpha cucumbers when fertigated with conventional hydroponic nutrient solution (Shaw et al., 2004). However, differences in yields exist between conventional hydroponics and aquaponics (Ayipio et al., 2019) mostly due to low nutrients, presence of solids, and high pH of AE. Thus, substrates that work well when fertigated with hydroponic solution might not adapt well with AE. Therefore, there is need to explore substrate suitability and performance in AE systems. We hypothesize that type of substrate used would affect availability of nutrients and thus cucumber productivity. Experiments were conducted to explore if pine bark and perlite substrates would influence Beit Alpha cucumber cv. ‘Socrates’ differently when fertigated with AE. The study also assessed the effect of plant number per pot and its interaction with substrate on cucumber productivity.

3.2 Materials and Methods

3.2.1 Plant material, growth conditions, and experimental design

All trials were conducted at the Auburn University aquaponic project facility located at E.W. Shell fisheries research station (lat.32.648935°N, long. 85.486828°W).

Plant production for the three seasons was done in a 9 m x 29 m double-layered plastic covered greenhouse. Three-week-old cucumber (*Cucumis sativus* L. 'Socrates') seedlings were transplanted from 70-cell trays to 11-L rectangular Dutch buckets (Crop King, Lodi, OH, USA) filled with either 100% horticultural grade perlite or aged pine bark based on the treatment. Over the course of the experiment, plants were trellised upwards to a height of approximately 2.2 m then allowed to drape.

The production in 2016 ran from January 6 to July 31 in two rounds of trials covering Winter-to Spring seasons. The first round of 2016 ran between Winter and early Spring while the second round covered the rest of the Spring months. The production in 2019 ran from September 3 to October 28 (late Summer-Fall), with a total of 55 days from transplanting. Plant spacing was 0.46 m x 1.83 m or 0.84 m^2/pot. During the 2019 trial, the greenhouse temperature, and relative humidity were measured using a pendant temperature data, and ext. temp/RH logger (HOBO, Onset Computer corp. Bourne, MA, USA) placed at 2.2 m from the ground, at the draping point. Data was logged every 10 minutes and averaged over 12-hour period. The greenhouse microclimate was considered important to assess the condition of growth of the plants. Although cooling of the greenhouse was done using exhaust fans and a cooling pad controlled by night and day temperature set points, temperatures and relative humidity still fluctuated throughout the production in 2019. The mean day and night air temperatures over the trial period for 2019 were 28.3 °C and 20.8 °C, respectively. Relative humidity was generally high. The mean day and night relative humidity values were 64% and 92%, respectively.

Water was delivered to the cucumbers via an irrigation pump with the corresponding foot valve submerged at 0.35 meters below the surface of a passive clarifier system attached to biofloc tilapia aquaculture unit as described below, such that the settleable solids further clarified in the bottom of the second clarifier were undisturbed. The irrigation pump was wired to a timer that was scheduled to water on the hour for 3 minutes each time for nine times per day. Iron chelate (13% EDTA Fe) was added at a rate of 2 mg L^{-1} to the second clarifier at monthly intervals.

The aquaculture unit used to irrigate the plants consisted of a 100 m^3 rectangular tank contained in 9 m x 29 m plastic greenhouse and a water clarifier unit consisting of two cylindro-conical tanks of 0.5 m^3 each located just outside the greenhouse. The fish tank was aerated by a 1-hp blower (SweetWater, Aquatic Eco-systems, Apopka, FL, USA) fixed with diffuser tubing. The blower was also used to create an airlift that circulated the water from the tank to the clarifier and back. Using normal operating procedures, effluent and solids from the fish rearing tank flowed into the first clarifier, from which settleable solids were removed 2 to 3 times daily by opening a clarifier drain. The AE then flowed by gravity to a second clarifier where further settleable solids were again removed and clarified effluent either flowed back into the fish tank or pumped into the vegetable greenhouse for irrigation. No other filtration devices were used with this system. Water pH was maintained in the range of 6-6.5 by adding $Ca(OH)_2$ directly to the fish tank. Potassium chloride was added to the fish tank to maintain a concentration of 120-

150 ppm when measured for chloride. Water into the fish tanks came from a rainwater fed reservoir and flowed by gravity to the fish tank as make-up water to account for plant use and water loss through evaporation and disposal of fish sludge.

Prior to starting the first experiment in 2016, the fish rearing tanks were in continuous operation to produce Nile tilapia (*Oreochromis niloticus* L.). Fish were cultured for 11 weeks and then graded, sorted, and stocked by size into three separate netted structures called hapas from where 50-75 kilograms of fish were harvested weekly. To jumpstart fish production, 750 tilapia of 200 grams each were stocked into a 6 m^3 hapa to be harvested first during the production cycle. Next 2,500 tilapia of 100 grams each and 7,000 tilapia of 50 grams each were stocked into separate 18 m^3 hapas to be cultured and eventually divided into an additional 100 m^3 tank. The fish were fed twice daily at 1.5% of their body weight with a complete diet of floating pellets containing between 40% and 36% protein (Cargill, Franklinton, LA, USA). Thus, the fish culture unit was a mix of different ages and weights that required different feed types and feeding rates.

A 2 x 2 factorial treatment arrangement in randomized complete block design with 4 replications per treatment was used leading to 16 experimental units in each season. The treatment combinations were as follows: Treatment 1: Perlite substrate with two plants per pot; Treatment 2: Perlite substrate with one plant per pot; Treatment 3: Pine bark substrate with two plants per pot; Treatment 4: Pine bark substrate with one plant per pot.

3.2.2 Measurements and Sampling for lab analysis (mineral composition)

Once harvesting was started in 2016, cucumber fruits were picked daily. Cucumber fruit count and fresh weights were recorded daily from five middle individual pots, for each experimental unit. In treatments with two plants per bucket, fruit numbers and weights were added together to represent count or weight per pot. In the 2016 trial, leaf samples were taken for foliar analysis at day 50 from transplanting. Fifteen recently matured leaves from each experimental unit were sampled. Leaf tissues were digested in sulfuric acid and analyzed for macro- and micronutrient concentrations using ICP-MS approach (Waters Agricultural Laboratories, Inc., GA, USA).

In addition to yield recorded in both 2019 seasons, measurements were taken on plant height measured at each destructive sampling for biomass, from just below the cotyledons to the apical meristems using a meter rule. Total nodes per plant were counted and divided by plant height to obtain average internode length. Leaf area was measured using LI 3100 (LICOR, Lincoln, Nebraska, USA). Leaf samples after area measurements were dried in an oven for minimum of 48 hours at 77 °C. Specific leaf area (cm^2 g^{-1}) per pot was calculated by dividing leaf area (cm^2) over leaf dry weight (g). Leaf SPAD index was measured with a portable SPAD meter (SPAD-502 plus, Spectrum technologies, Aurora, IL, USA) at five points on newly fully expanded leaves and averaged. Leaf stomatal conductance was measured on the same leaves used for SPAD measurements using a handheld leaf porometer (Decagon SC-1, Meter Group, Inc. Pullman, WA, USA). Plants were placed on a raised platform constructed using cinder blocks and a fiberglass frame. Containers (4.7-L) were placed below plants to collect leachate daily from which pH and EC were measured using a HI9813-6 Portable pH/EC/TDS/temperature meter (Hanna Instruments, Smithfield, RI, USA) and NO_3^- using a L-AQUA twin handheld meters (Horiba, Kyoto, Japan) and multiplied by 0.22 to obtain NO_3^- -N.

Nitrogen use efficiency was calculated based on the measured nitrate of the AE. Daily nitrate measurements were average over the period, and together with the irrigation schedule

(7:00 am to 6:00 pm CDT), discharge rate of 3.785 L h^{-1} (Pickens, 2015) the amount fertigated over the period was estimated as;

$$A_f = D/60 \times r \times E \times T_p \times N_c \qquad (1)$$

Where; A_f = Amount fertigated, D = duration (minutes) per irrigation event, r=discharge rate, E=number of events per day, T_p = duration of trial, and Nc=NO_3-N concentration.

The nitrogen use efficiency was then estimated by dividing total yield (kg) over amount of NO_3-N fertigated (kg)

3.3 Data Analysis

Data were subjected to analysis of variance (ANOVA) using the GLIMMIX procedure in SAS (SAS Institute, Cary, NC, USA). Block and individual sampling units were considered as random variables. For yield and foliar data across seasons in 2016, a three-way ANOVA including substrate, density, and season was used. However, for measurements that were taken in 2019, a two-way ANOVA of substrate by density was used. Post-hoc mean comparison was done using Tukey’s HSD at $\alpha = 0.05$.

3.4 Results and discussion

3.4.1 Aquaculture effluent and substrate leachate nitrate concentration, pH, and EC

The weekly averages of nitrate-N, pH, EC over the experimental period for 2019 are shown in **Table 3.1.** Overall, nitrate-N fluctuated the most, ranging from 59.4 ppm to 77.3 ppm in the AE. The highest average weekly EC was 1.24 mS cm^{-1}. The lowest weekly average pH was 6.17 and reached a maximum at 6.7. Measurements of leachate pH, nitrate, and EC allowed the determination of effect of each substrate and planting density on these parameters. In the first configuration, leachate was collected in a non-replicated manner, which was difficult to determine statistical effects of the substrate and/or density on leachate parameters. However, the setup in 2019 allowed leachate collection from individual experimental units and a test of treatment effect (**Table 3.2**).

Leachate pH was higher in perlite than pine bark by about 9% irrespective of plant density but was not statistically significant. However, difference in leachate EC between the substrates depended on plant density such that for one plant per pot, no significant difference existed between the two substrates whereas for two plants per pot, perlite recorded significantly higher leachate EC (12.9%) than pine bark (Table 3.2). There was no main effect of substrate, and density or their interaction on leachate nitrate-N concentration. Generally, the EC of leachate collected from the pots was averagely lower than the effluent EC from the fish tanks, indicating a possible effect of plant nutrient uptake and/or substrate, especially for pine bark, on leachate EC.

Table 3.1. Weekly AE NO_3-N, pH, and EC supplied from the aquaculture unit. Daily measurement for 2019 trial from the emitter and averaged over a 7-day period

Week After Transplanting	NO_3-N (ppm)	pH	EC (mS cm^{-1})
Week1			
Mean	61.05±3.3	6.4±0.15	1.08±0.00
N	4	4	4
Week2			
Mean	62.54±4.9	6.2±0.14	1.09±0.09
N	7	7	7
Week3			
Mean	77.31±3.7	6.3±0.21	1.24±0.15
N	7	7	7
Week4			
Mean	69.14±7.6	6.5±0.22	1.01±0.14
N	7	7	7
Week5			
Mean	61.60±11.9	6.7±0.27	1.18±0.39
N	7	7	7
Week6			
Mean	75.43±17.0	6.5±0.34	0.98±0.25
N	7	7	7
Week7			
Mean	61.6	6.7±0.27	1.13±0.20
N	6	6	6
Week8			
Mean	59.4±4.4	6.6±0.10	1.12±0.16
N	3	3	3

Table 3.2. Simple effects of substrate for each planting density level on leachate NO3-N, pH, and EC. Data collected from Dutch bucket drainage in 2019

Density^z	Substrate	NO_3-N (ppm)	pH	EC (mS cm^{-1})
1x				
	Pine bark	68.91a	6.07b	0.81a
	Perlite	77.11a	6.66a	0.87a
	P-value	*0.4351*	*<.0001*	*0.1942*
2x				
	Pine bark	59.29a	6.13b	0.74b
	Perlite	74.17a	6.61a	0.85a
	P-value	*0.1683*	*<.0001*	*0.0169*

^{z}1x = one plant per pot; 2x = two plants per pot; pot=11-L Dutch bucket.

3.4.2 Foliar nutrient analysis of cucumber affected by substrate and density

The results showed that foliar nutrient concentration of the plants grown in either pine bark or perlite substrates did not differ significantly (p>0.05). Also, number of plants per pot did not significantly affect foliar nutrient composition of the leaves. However, plants grown in Winter-Spring 2016 had higher N, P, K, and Mg values than those in Spring except for Ca and S. Foliar nutrient concentration was higher than sufficiency range for N, P, Ca, and S but not K and Mg which were below the sufficiency ranges. Foliar micronutrient concentrations were generally within reported sufficiency ranges except for B which was at or below the low side of the reported sufficiency range across all treatments in 2016. The nutrient levels in our system are far below the recommended levels for cucumber production (Mills and Jones Jr, 1996) which corroborates other studies showing that AE is low in plant essential nutrients, especially micronutrients (Bittsánszky et al., 2016), resulting in low yields of aquaponics systems compared to conventional hydroponics system when there is no nutrient supplementation in the AE (Ayipio et al., 2019). However, even when two plants were grown per pot, we observed no signs of nutrient deficiency indicating superior performance amidst the low nutrient load. The interesting observation of sufficient foliar nutrient concentration in this study was also reported by Blanchard et al. (Blanchard et al., 2020) where regardless of pH adjustment, cucumber had sufficient foliar nutrient concentration. There needs to be further investigation into what accounts for this performance. We hypothesize that the presence of solids in the AE could play a role in the availability of nutrients through mineralization over time. Also, the biological floc which is characteristic of the biofloc system could be a better source of nutrients than clear water systems as was demonstrated by Pinho et al. (Pinho et al., 2021) which previously led to better growth of lettuce in biofloc tilapia system (Pinho et al., 2017). We anticipated that pine bark, due to its organic nature would lead to enhanced mineralization and thus nutrient availability than perlite which is inorganic in such biofloc systems. Also, we posited that since pine bark generally has lower pH than perlite, it would present a better substrate level pH adjustment to the AE which is usually maintained at higher pH to favor the fish and nitrifying bacteria. However, our observations showed that although there are isolated cases of higher foliar nutrient content in pine bark than perlite, this is not a general case. The effect of pine bark on pH could however be responsible for the observed spikes in foliar Mn content in Spring 2016 which was above the upper sufficiency levels. Manganese availability is easily influenced by pH and therefore, since pine bark has lower pH than perlite, this could have led to a higher competitive advantage of Mn than the other divalent cations such as iron in the pine bark substrate. However, these spikes could be potential source of phytotoxicy (Maher and Thomson, 1991).This is due to an attempt by the plant to balance its ionic charge concentration especially when iron (Fe^{2+}) is limiting. Foliar B concentration was lower than the lower sufficiency limit in almost all cases except for pine bark in spring 2016. Boron availability is also dependent on pH which must be below 6.0, preferably between 4.5 and 5.5 for maximum availability (Maucieri et al., 2019). In this case, B sufficiency was favored under the low pH condition of pine bark which is supported by the leachate measurement taken in 2019 (**Table 3.2**).

Table 3. 3. Effect of substrate and planting density on foliar macronutrient concentration (g 100 g^{-1} dry mass) of 'Socrates' cucumber in two trials in 2016.

	N	P	K	Mg	Ca	S
			Winter-Spring 2016			
Substrate						
Pine bark	5.26	0.86	2.63	0.43	2.07	0.55a
Perlite	5.16	0.8	2.62	0.42	2.04	0.49b
P-value	*0.4313*	*0.2284*	*0.9796*	*0.8356*	*0.9153*	*0.0197*
Density^{z}						
1x	5.25	0.86	2.70	0.44	2.06	0.53
2x	5.18	0.8	2.55	0.42	2.05	0.51
P-value	*0.6028*	*0.195*	*0.2956*	*0.384*	*0.9636*	*0.2322*
			Spring 2016			
Substrate						
Pine bark	4.44	0.61	2.11	0.42	4.06	0.66
Perlite	4.45	0.57	2.14	0.43	4.21	0.6
P-value	*0.9697*	*0.5708*	*0.8397*	*0.8091*	*0.5778*	*0.2014*
Density						
1x	4.43	0.6	1.98	0.44	4.23	0.63
2x	4.47	0.6	2.27	0.41	4.04	0.63
P-value	*0.8694*	*0.9954*	*0.075*	*0.1828*	*0.4921*	*0.9772*
Sufficiency level^{y}	4.3	0.3	3.1	0.35	2.4	0.32

^{z}1x = one plant per pot; 2x = two plants per pot; pot=11-L Dutch bucket.

^{y}Lower sufficiency level from Mills & Jones Jr (Mills and Jones Jr, 1996)

Table 3.4. **Effect of substrate and planting density on foliar micronutrient concentration (mg kg-1 dry mass) of 'Socrates' cucumber in two trials in 2016**

	B	Fe	Mn	Cu	Zn
		Winter-Spring 2016			
Substrate					
Pine bark	19.55	69.32	99.37a	9.75a	67.3a
Perlite	22.02	67.13	71.25b	8.67b	58b
P-value	*0.0893*	*0.5552*	*0.0205*	*0.0413*	*0.0246*
Density^{z}					
1x	21.43	69.23	88.53	9.23	61.95
2x	20.13	67.22	82.08	9.18	63.35
P-value	*0.327*	*0.5849*	*0.5004*	*0.9088*	*0.6695*
		Spring 2016			
Substrate					
Pine bark	30.66	79.49	215.59	7.68	79.75
Perlite	27.2	74.68	193.25	8.088	80.36
P-value	*0.1214*	*0.6239*	*0.2067*	*0.3942*	*0.9221*
Density					
1x	28.83	79.20a	213.5	7.73	84.43
2x	29.04	74.96a	195.34	8.038	75.69
P-value	*0.9187*	*0.6654*	*0.2972*	*0.5149*	*0.1851*
Sufficiency levels^{y}	30	50	50	8	25

^{z}1x = one plant per pot; 2x = two plants per pot; pot=11-L Dutch bucket.
^{y}lower sufficiency level from Mills & Jones Jr (Mills and Jones Jr, 1996)

3.4.3 Yield and yield components of cucumber due to substrate and density effect

Total yield in 2019 was low due to an early termination of the trial. Maximum yields in 2019 were 3.7 kg m^{-2} and 5.5 kg m^{-2} for one plant per pot and 6.7 kg m^{-2} and 7.1 kg m^{-2} for two plants per pot respectively recorded by pine bark and perlite (data not shown). Differences in fruit yield in 2019 was not significantly affected by substrate but plant density (**Table 3.5**). The yield advantage of two plants per pot over one plant per pot in 2019 was 63% on a square meter basis. Yield in 2016 were higher with maximum values ranging from 16.5 kg m^{-2} in one plant per pot to 24.3 kg m^{-2} in two plants per pot. Analysis of variance conducted on only 2016 yields showed that season had no significant main effect on cucumber yield ($p>0.05$). However, there was a significant three-way interaction among season, planting density, and substrate. In Winter-Spring season of 2016, plants grown in perlite substrate recorded 2 kg m^{-2} (±0.917; SE) less yield than those grown in pine bark for one plant per pot, although the effect was not statistically significant ($p=0.15$). However, in Spring 2016, perlite recorded statistically significant (adjusted $p=0.040$) more yield (2.29 kg m^{-2}) than pine bark for two plants per pot. The average yields across seasons are shown in **Figure 3.1**.

Effect of the substrates on yield difference is not direct but due to effect on nutrient availability and uptake because of substrates physical, chemical, and/or biological properties which affect the root environment. On the other hand, number of plants per pot would influence aboveground parameters which relate to light interception for photosynthesis (Xiaolei and Zhifeng, 2004). The interaction between nutrient and water availability due to the substrate effect and aboveground factors due to effect of number of plants per pot, was anticipated to translate into effect on yield. In terms of productivity of the crop, our results showed that both substrates had similar influence on cucumber yield which was Similar to observations made by Shaw et al. (Shaw et al., 2004). In our case, pine bark only showed superior yield performance over perlite in one plant per pot. This means that the increased above and below ground mass due to the additional plant number did not offer benefit for pine bark substrate in the inherently low nutrient AE. Pine bark is known to be high in potassium (Maher et al., 2008) which is an essential nutrient for fruit development. In cucumber, potassium is especially required in increased concentrations at heavy fruiting stage. Therefore, the high potassium contained in pine bark coupled with its relatively higher cation exchange capacity of 10 cmol L^{-1} (Silber, 2008) than perlite was expected to confer superior yield performance in both plant densities. It is not known why there was a reduction in fruit yield for pine bark in two plants per pot. Probably, high bulk density which is characteristic of pine bark had restricted growth effect on two plants per pot. There are few studies examining cucumber performance in different substrates fertigated with AE in the literature making it difficult to examine the performance of the two substrates in view of other studies. However, substrate-based had systems resulted in poor yield comparison between aquaponics and conventional hydroponics crop yield with fewer studies using substrates, indicating that more research on substrate use with AE is required (Ayipio et al., 2019). For cucumber fertigated with hydroponic nutrient solution, performance in different substrates is affected by the substrate's ability to retain water and was demonstrated by improvement in marketable yield by wood bark when combined with peat (Peyvast et al., 2010).

Although our data show that two plants have overall more yield per square meter than one plant per pot, this data is not sufficient to conclude on economic productivity of two plants per pot when fertigated with AE. Other economic factors such as added labour and seed cost must be considered. We realized that on a per plant basis, there was no significant effect of number per pot on yield indicating lack of mutual benefit of the added leaf foliage to improve yield. Yields obtained in 2019 were generally low for cucumbers grown for 35 days from transplanting due to an early termination of the experiment resulting from observed foliar damage from disease spores. Even the low yields obtained in 2019, results compare well with an earlier study in the same system (Pickens, 2015) where cucumber plants were grown for 44 days from transplanting.

Table 3.5. **Substrate-Season and Density-Season interaction effect on cucumber fruit yield**

	Yield (kg m^{-2})		
	Winter-Spring 2016	Spring 2016	Spring-Summer 2019
Substrate			
Pine bark	13.26Aa[z]	11.17Aa	3.37Ba
Perlite	12.52Aa	12.03Aa	3.90Ba
Density[y]			
1x	10.39Ab	9.73Ab	2.91Ba
2x	15.38Aa	13.46Aa	4.37Ba

[z] Means in the same column followed by the same lower-case letter are not statistically different (P³0.05); means in the same row followed by the same upper-case letter are not statistically different. Means under ‘Substrate’ are not compared with means under ‘Density’

[y] 1x = one plant per pot; 2x = two plants per pot; pot=11-L Dutch bucket.

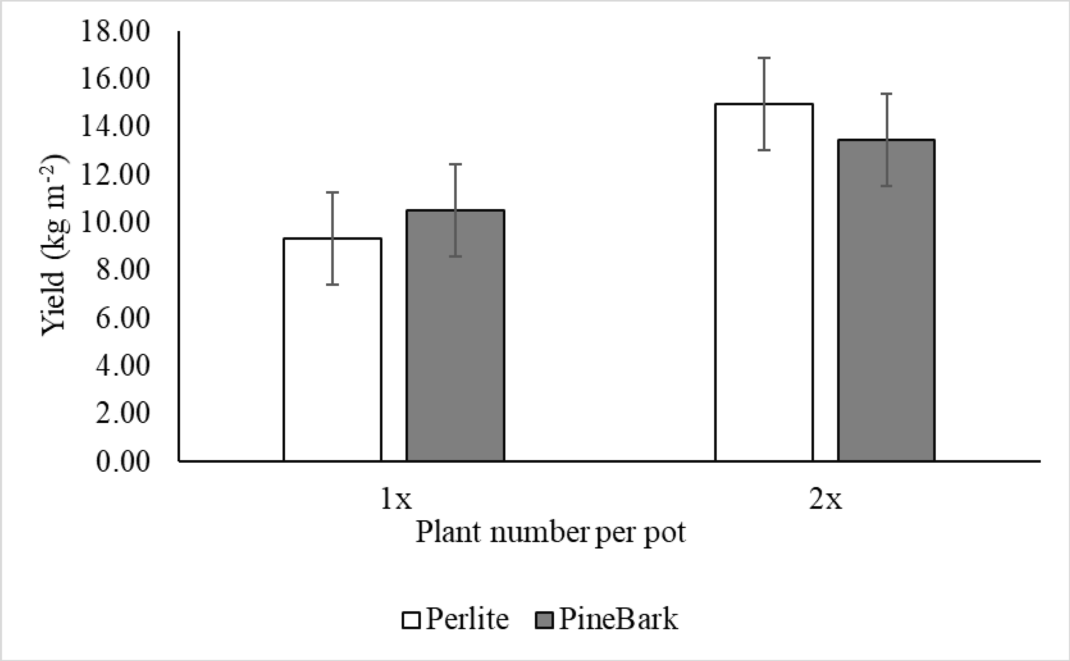

Figure 3.1. Yield per square meters of cucumber in 2016 trial across seasons of Spring and Winter-Spring, 2016. Error bars are ± standard error. 1x=one plant per pot; 2x=two plants per pot**.**

3.4.3 Morphological measurements

In the 2019 trial, SPAD value was used as a proxy assessment of the overall health of the plants since there was no foliar nutrient content analysis. Mean SPAD values were 23.27 and

25.77 in one plant per pot whereas for two plants per pot, SPAD values were 24.73 and 25.98 for perlite and pine bark, respectively. Generally, plants grown in pine bark had significantly higher SPAD values than those in perlite by about 1 SPAD unit which is considered low in terms of horticultural importance. SPAD value of 45.2 SPAD units is considered sufficient to predict yields for cucumber (Padilla et al., 2017). Therefore, the low SPAD values recorded in 2019 could also explain the low yields recorded in that year. Leaf area and dry weights were used to estimate specific leaf area (SLA) which is usually an essential input for leaf area index conversion when modeling light interception. The SLA of cucumber plants grown in the system ranged from 249.69 to 430.35 cm^2 g^{-1} which was similar to that found in fruiting cumber plants for restricted and non-restricted roots at 60 days after sowing (Kharkina et al., 1999). Low SLA values are an indication of high leaf dry matter content as a result high light level. It was expected that SLA be high in two plants per pot due to competition for light. However, our results showed no significant effect of number of plants per pot on SLA indicating similarity in light environment for both configurations. Mean Stomata conductance values were 712.4 and 696.1 mmol $[H_2O]$ m^{-2} s^{-1} in perlite but were 674.0 and 729.22 mmol $[H_2O]$ m^{-2} s^{-1} in pine bark for one plant and two plants per pot, respectively. However, there was no significant interaction between substrate and number of plants per pot on stomata conductance. The values obtained for stomata conductance are similar to values obtained for cucumber infested with powdery mildew even with full strength nutrient supply (Wang et al., 2020). This stomata response was because of the greenhouse growing condition of high humidity and temperature but not due to treatment effects. However, it was evident that in pine bark substrate, growing two plants per pot exacerbated the situation as seen in the reduction of stomata conductance. The low stomata conductance is an additional explanation for the low yield observed in 2019 because, stomata opening is necessary for both transpiration and leaf photosynthesis. Leaf area index (LAI) values were also low with highest LAI being 3.0 m^2 m^{-2} and lowest of 1.07 m^2 m^{-2} at 35 days after transplanting with more than 16 leaves. For optimal cucumber productivity, LAI of greater than 3.5 m^2 m^{-2} is estimated for more than 16 leaves per plant (Xiaolei and Zhifeng, 2004). This means the current LAI estimated from our study is not optimal for cucumber productivity. However, Nikolaou et al. (Nikolaou et al., 2017) obtained maximum LAI value of 1.84 m^2 m^{-2} at 43 days after transplanting in greenhouse soilless cucumber grown with cooling indicating our results are not an isolated case.

3.5 Conclusion

We can conclude that generally, although the biofloc AE was low in dissolved ions, it was successful for growing the Beit Alpha cucumbers and had comparable yields between the two substrates assessed. Foliar nutrient concentrations were generally within sufficiency ranges except foliar B which was lower. Pine bark showed effect on reducing leachate pH and could be used as a pH downward regulator in AE for downstream. Effect of the substrates on yield was dependent on season and number of plants per pot. Use of pine bark as substitute substrate for perlite is only justified in one plant per pot when density is increased to two plants per pot, perlite is more preferrable.

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Chapter IV

4.0 Effect of fertigation interval and duration on growth, and yield of cucumber grown with hydroponic nutrient solution

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Abstract

Timer-clocks are used to schedule irrigation, and when coupled with an injection system, also provide dissolved nutrients to plants at preset intervals and durations. Preset intervals and durations affect leachate fraction and crop productivity due to fertigation volume. Two different experiments were conducted to assess effects of fertigation interval or duration separately on cucumber (*Cucumis sativus* L.) growth and yield, and leachate characteristics. The experimental design in each case was a randomized complete block with four replications. In the first experiment cucumber performance was evaluated under four fertigation scheduling intervals viz: 15, 30, 60, or 90 minutes at a fixed duration of 4 minutes. In the second experiment cucumber performance was evaluated for four fertigation durations viz: 1, 2, 3, and 4 minutes at a fixed interval of 30 minutes. Increasing fertigation interval led to increased leachate EC, nitrate-N and K^+ concentration. However, it was observed that apart from leaf sulfur content which was highest at 30-minute interval and lowest at 60-minute interval, tissues macronutrients content partitioned in leaves, shoots, and fruits remained the same across fertigation intervals. Also, fertigation interval failed to significantly influence cucumber growth and yield whereas water use efficiency significantly increased with increasing fertigation interval. Therefore, due to the increased crop water use efficiency and linear reduction in leachate volume with increasing intervals, fertigating every 90 minutes for the 4-minute durations was identified as the most efficient fertigation interval. Results from fertigation duration trial at a half-hourly interval showed no effect on total aboveground tissue macronutrients content. However, fertigation duration influenced tissue iron (Fe) copper (Cu) and boron (B) contents and promoted highest tissue Fe and B at 3-minute duration whereas highest tissue Cu content was recorded at 1-minute duration. Therefore, choice of a particular fertigation duration did not affect the overall nutrition of the plants albeit differences existed in uptake of different elements. Yield response to fertigation duration was significantly different depending on experimental run. The highest yield of 5.12 kg plant^{-1} was recorded at 2-minute duration in experimental run 1 whereas highest yield of 3.58 kg plant^{-1} was recorded at 1- or 4-minute duration in experimental run 2. The observations indicate that if a higher fertigation frequency of 30-minute interval is to be used, then fertigation duration could be reduced to 1 minute without significant yield penalties.

Keywords: nutrient injection, leachate measurements, cucumber nutrition, leaf photosynthesis.

4.1 Introduction

The global population is estimated to reach 9 billion people by 2050 (UN, 2019) which means food production must meet the growing demand. However, increased food production must also safeguard the environment by reducing pollution. Therefore, management strategies that reduce negative environmental impact and improve usage efficiencies of natural resources must be adopted. Fertigation is one of the approaches used in greenhouse vegetable production to manage water and dissolved nutrients in a manner that optimizes nutrients and water use without environmental consequences. Since the advent of the drip irrigation system further strives have been made to optimize water use efficiency especially in greenhouse soil-based production whilst reducing environmental impacts (Abalos et al., 2014; Liang et al., 2014, 2014; Wang et al., 2019). Irrigation management is even more important in substrate-based production especially where most of the substrates used such as perlite are porous in nature and results in leaching of nutrients such as nitrogen (Groenveld et al., 2019). Irrigation coupled with fertilization is referred to as fertigation in which water soluble fertilizers at recommended concentrations required by crops are conveyed with every irrigation time or at discrete intervals through the irrigation stream to the root zone (Papadopoulos, 2001). This means that meeting the crop water demand will also influence the nutrient amount supplied to the plants. Therefore, fertigation management is a serious issue especially in open systems, also called drain-to-waste where leachate is not captured for reuse. In drain-to-waste systems, fertigation must meet the crop water and nutrients demands whilst reducing wastage to safeguard the environment (Liang et al., 2014). Meeting the crop water demand in containerized systems involves making water available when needed by the crop. In containerized-media systems, water availability is defined as the capability of the growing medium to supply the atmospheric demand at compatible rate (Wallach and Raviv, 2005). This implies, water supply must match up with daily vapour pressure deficit (VPD) which drives water uptake. Since water uptake affects nutrient uptake, fertigation attempts to simultaneously supply adequate water and nutrients to meet daily uptake.

Most approaches to irrigation, and by extension, fertigation management involves use of sensors to monitor the crop, growing environment, and/or growing medium which allows to assess the crop water needs and supply as required. However, these technologies that accurately monitor and control inputs are prohibitively expensive or complicated and many growers opt for the lower cost, less expensive option. Also, models of irrigation and nutrition management becomes undesirable due to their highly complicated nature and need to estimate many system specific parameters (Klaring, 2001). Thus, most growers would use simple automated approaches such as a timer-clock to manage irrigation/fertigation. Timer-clocks aids in reducing labor requirements for daily irrigation/fertigation as they can be set to irrigate/fertigate at fixed time intervals within the day but could be wasteful (Lieth and Oki, 2008). Timing intervals and duration are scheduled by programming the timer-clock to deliver water/nutrient solution at certain preset time points for a certain period within the day or night as desired. Timing of irrigation/fertigation is a necessary approach to scheduling even if there is perfect knowledge of plant water requirements (Stanghellini et al., 2019).

Fertigation management is very important in greenhouse cucumber production because, yield of the crop is influenced by fertigation amount and shown to increase with increasing fertigation level (Lee et al., 2005). In soilless cucumber production, yields are affected by fertigation amount (Singh et al., 2019) which has impacts on economic potential of the crop (Chand Singh et al., 2018). Highest yield of 3.29 kg plant^{-1} were recorded for soilless cucumber when fertigated with 100% recommended hydroponic nutrient solution in naturally ventilated greenhouse (Singh et al., 2019).

Optimal daily fertigation in cucumber is necessary to reduce migration of salts in the soil and improve yield of the crop (Liang et al., 2014) especially in soilless systems where porous substrates with low water holding capacity are used. Even when fertigation is based on integrated solar radiation, drainage rates rapidly increase when cucumber grows in perlite (Roh and Lee, 1996). Since timer-clocks provide a haven for small scale growers due to economic reasons, there is need to investigate how reducing fertigation volume through increasing intervals or duration could contribute to managing leached nutrients while safeguarding cucumber yield. Thus, this research provides in part a way to improve efficiency for growers without having to adopt overly expensive or complicated methods. Therefore, studies were conducted to assess effect of fertigation interval and duration in cucumber growth and yield and leachate measurements in perlite substrate.

4.2 Materials and Methods

4.2.1 Description of location and crop management

In both fertigation interval and duration trials, experiments were conducted in a double-layered plastic-covered greenhouse at Auburn University E.W. Shell fisheries station, aquaponics project site. The fertigation interval trial was conducted in one experimental run lasting from 9/21/2020 to 11/9/2021. The fertigation duration trials were conducted in two sets of experimental runs lasting from 1/22/2021 to 4/15/2021 and 4/13/2021 to 6/16/2021 for experimental run 1 and run 2, respectively.

4.2.2 Cucumber cultivation

In both interval and duration trials, cucumber (*Cucumis sativus* L. ‘Delta star’) seeds were raised in 72-count round (58 mL) cells styrofoam seeding trays (Hydrofarm, Pentaluna, CA) filled with commercial germination potting mix (Miracle-Gro®, The Scotts LLC, CA, USA). Trays were placed under greenhouse conditions and watered to keep media moist. Three-week old uniformly strong seedlings were transplanted into 11-L rectangular Dutch buckets (Crop King Inc., Lodi, Ohio) filled with 100% horticultural grade perlite media, single plant per pot maintained at a density of 3.6 plants m^{-2} (0.30 m × 0.91 m) for both fertigation interval and duration trials. All plants were trained to one stem per plant by pruning all lateral growth and were vertically trellised using plastic clips (Bato bobbins, Crop King, Lodi, Ohio) along a twine that was attached to a horizontal cable suspended about 4 m above ground level to serve as support. The first four fruits from the base of the plant were removed to encourage early vegetative growth. Starting at the fifth node, fruits were allowed to reach maturity and were harvested three times per week. All foliage including and below the third node below the oldest fruit was removed regularly.

4.2.3 Greenhouse climate condition

4.2.3.1 Duration trials

Light (lux), air temperature, and relative humidity were measured using a pendant temperature/light logger, and temp/RH logger (HOBO®, Onset Computer corp. Bourne, MA, USA) respectively, placed at the terminal height of the canopy. Light measurements were converted to photosynthetic photon flux density (PPFD) by multiplying lux units with a conversion factor 0.0185. The greenhouse climate variables during the duration trials are summarized in **Table 4.1.**

Table 4.1. Greenhouse climate conditions during fertigation duration trials

			Temperature sum (°C)					
WAT[v]	Light sum (µmol m^{-2} s^{-1})[y]		Max		Min		Relative humidity (%)[z]	
	Run1[u]	Run2	Run1	Run2	Run1	Run2	Run1	Run2
1	5407	17224	158	330	851	196	.	68
2	12056	17766	262	305	112	175	.	60
3	9284	18046.	239	304	127	180	.	72
4	13560	18123	279	296	119	178	.	76
5	10349	15701	245	302	131	193	.	84
6	11699	18403	254	316	132	196	.	85
7	13044	.	261	.	126	.	.	
8	16377	.	318	.	148	.	.	
9	100305	.	208	.	94	.	.	
Grand Total	101806.49	105263.43	2224.55	1853.01	1072.77	1116.91	.	

[z] Relative humidity (RH) was logged every 30 minutes. The RH values were averaged over the period. There was no RH measured for run 1 due to dysfunctional data loggers

[y] Light was measured with using a pendant temperature/light logger in lux and converted to photon flux density by multiplying with the conversion factor 0.018. Light values are sum (integral) on a weekly basis

[v] WAT = weeks after transplanting

[u] run 1 lasted from 1/22/2021 to 4/15/2021 and run 2 lasted 4/13/2021 to 6/16/2021

4.2.4 Fertigation and leachate collection

The amount of nutrient solution supplied per container was estimated using Eqn. 1. The emitter discharge rate was determined by measuring volume of 10 sampled emitters at the table height and timed the period taken to reach that volume. Discharge rate calculated was seen to be higher than the commercial rating for the emitters. For irrigation delivery, there was a main irrigation line connect to solenoids valve which open and close based on the set time. Lateral irrigation lines were then connected to the main lines from which spaghetti tubing were connected to the emitters to deliver fertigation solution to each plant. In both interval and duration trials, chemical fertilizers were injected directly into the irrigation water system using a series of proportional injectors (Dosatron, QC supply, Schuller, NE, USA) which allowed for setting injection ratio (Error! Reference source not found.**A**).

Irrigation volume (L pot^{-1}) = discharge rate (L h^{-1})×duration of irrigation (h) **eqn.1**

For leachate collection, all pots (Dutch buckets) were placed on a platform constructed, using fencing poles and hangers, to raise containers above the ground (75-77 cm, low-high with about 1% slope) and to enable leachate collection and measurement (Error! Reference source not found. **B**). To collect leachate from plants, 5-gal. (18.9 L) buckets were placed under the platform. Leachate measurements in both interval and duration trials was done on the most middle pot, 1 pot per experimental unit. Measurement of leachate was done using a graduated bucket and. Irrigated and leachate solution pH and EC, and nitrate were measured with HI9813-6 Portable pH/EC/TDS/Temperature Meter (Hanna Instruments, Smithfield, Rhode Island). and L-AQUA twin handheld meters (Horiba, Kyoto, Japan) respectively prior to volume measurement. In **Figure 4.1**, In panel A, injection system consisted of 2 Dosatrons **(**D14MZ2). Stock A contained complete fertilizer (Jack's nutrients, N-P-K-5-12-26) plus KO_3 (Multi-K GG potassium nitrate, N-0-K 13-46) plus $MgSO_4^-$(Magriculture Heptahydrate Epsom salt, 9.8% Mg, 12.9% S) and Stock B contained Calcium nitrate (YaraLiva Calcinit, 15.5-0-0 N-P-K+19% Ca). In panel B, the 2" white PVC pipes were used as return pipes for uncollected leachate to outside of the greenhouse. The leachate was collected with the blue buckets located under the platform whilst the black pipes on the platfrom were the irrigation lines carrying nutrient solution connected with Spaghetti tubing and 1 gal h^{-1}, pressure compensated Bowsmith emitters to deliver nutrient solution with concentrations indicated in **Table 4.3** to each plant.

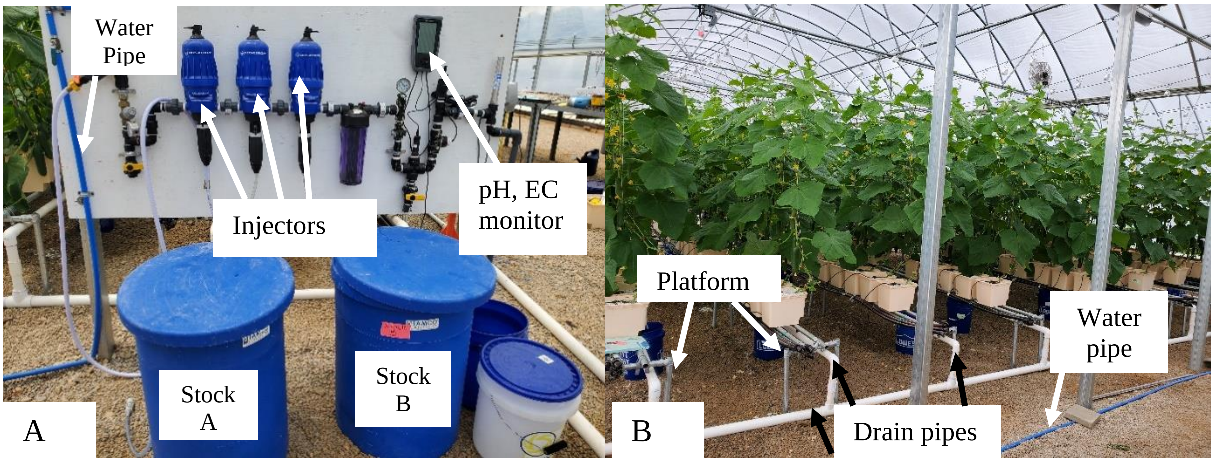

Figure 4.1 Nutrient injection system (A) and Sectional pictorial view of setup with plants (B).

4.2.4.1 Interval trial

The estimated volume for each fertigation interval is indicated in **Table 4.2**. The target nutrient concentrations for the interval trial and experimental run 1 of the duration trial are displayed in **Table 4.3.** Each interval was controlled by a single watering station on the timer clock so that when it is on, every line in all blocks were fertigated at the same time.

Table 4.2. Estimated fertigation volume for each fertigation interval per plant per day.

Interval (minutes)^{z}	Events plant^{-1} day^{-1}	volume based on emitter rating (L plant^{-1}day^{-1})^{y}	volume based on calculated discharge (L plant^{-1} day^{-1})^{x}
15	38	9.59	18.24
30	22	5.55	10.56
60	12	3.03	5.76
90	8	2.02	3.84

^{z}duration per event = 4 minutes
^{y}discharge expected=3.785 L h^{-1}
^{x}average discharge calculated=7.2 L h^{-1}

Table 4.3. Target nutrients for fertigation interval and duration trial run 1

	Target Concentrations (ppm)	
Nutrient	set 1[z]	set 2
NO3-N	180.48	181.31
P	103.18	134.13
K	255.80	332.54
Ca	151.00	120.80
Mg	131.07	170.40
S	169.50	220.35
Fe	3.00	3.90
Mn	0.50	0.65
Zn	0.15	0.20
Mo	0.19	0.25
Cu	0.15	0.20
NH4-N	8.94	7.15

[z] In interval trial, set 1 lasted from 0 to Harvest 5, and set 2 from Harvest 5 to final; in duration trial; set 1 lasted from 0 DAT to Harvest 1 and set 2 till final harvest

4.2.4.2 Duration trial

The fertigation volume supplied by each duration per plant per day is displayed in **Table 4.4** and the nutrient concentrations are displayed in **Table 4.5**. The same procedure used in estimating the volume in the fertigation interval trial was employed here. However, fertigation duration treatments started from first day after transplanting. Leachate collection was done as described for fertigation interval experiment. However, in experiment run 2 which started from 4/13/2021 to 6/16/2021, leachate collection was done at discrete intervals (three times per week). Leachate was collected for a period of two days and the total volume was then measured.

Table 4.4. Estimated discharge and daily fertigation volume for each duration.

Duration	discharge (L h^{-1})	Volume (L d^{-1})
1	11.5	4.6
2	8.2	6.6
3	6.8	8.2
4	6.6	10.5

Table 4.5. Target nutrient concentrations of duration trial, run 2

	Target concentration (mg L^{-1})	
Nutrient	0 to 25 DAT	26 DAT to final harvest
N (NO3-N + NH4-N)	196.4	186.1
P	52.4	52.4
K	250.0	300.0
Ca	190.0	150.0
Mg	90.0	90.0
S	120.5	120.5
Fe	3.0	3.0
Mn	0.5	0.5
Zn	0.2	0.2
Mo	0.2	0.2
Cu	0.2	0.2
B	0.5	0.5
NH4-N	11.3	8.9

4.2.5 Treatments and experimental design

4.2.5.1 Interval trial

Fertigation timing intervals of 15, 30 (control), 60 or 90 minutes at a fixed duration of 4 minutes throughout the crop cycle. The intervals were chosen to reflect practices in soilless cucumber production. In the literature, only one study was found to have used fixed time interval and scheduled every 3 hours and duration maintained at 5 minutes. Irrigation water volume was found to be inadequate in meeting the water requirements of pepper (Rahman et al., 2018). Also, because perlite has high drainage rates with cucumber (Roh and Lee, 1996), fertigation intervals or duration selected needed to take account of drainage. Scheduling was achieved by connecting solenoid valves to programmed timer-clocks (Sterling 12, Buckner Superior, Storm Manufacturing Group, Inc., Normandie Avenue Torrance, CA, USA). There were for blocks for each fertigation interval resulting in a total of 16 experimental units. Each experimental unit consisted of 10 pots resulting in a total of 160 plants for the whole trial.

4.2.5.2 Duration trial

The fertigation duration treatments were 1, 2, 3, or 4 min at a fixed interval of 30 minutes. The fertigation duration trial was also laid out in the randomized complete block design with four replicates. An experimental unit in this case consisted of 5 plants with a total of 80 plants and the middle 3 plants per experimental unit were used for data collection.

4.2.6 Measurements of plant traits

4.2.6.1 Interval trial

Plant height was measured from substrate level (base of the plant) to the apical meristem using a meter rule. Number of nodes were determined by counting nodes on the main stem starting from the lowest node to the top of the most apparent node through visual assessment. Samples of leaves, stems, and fruits were taken to determine tissue elemental contents. Leaf samples were oven dried at 105 °C for 48 h whilst fruit samples were dried for up to 1 week. Tissue analysis of plant parts for macro-and micronutrients was a using Inductively Coupled Plasma-Emission Spectroscopy (ICP_ES) via the AOAC official method 985.01 (AOAC, 2012) at Waters Agricultural Laboratory in Camilla, Georgia. In the fertigation interval trial, leaf area was measured from leaves sampled for nutrient analysis using a leaf area meter (LI-COR 3100®, LI-COR Biosciences Lincoln NE, USA). Specific leaf area ($cm^2 g^{-1}$) per pot was calculated by dividing leaf area (cm^2) over leaf dry weight (g). Leaf chlorophyll was measured with a portable

Soil Plant Analysis Development meter (SPAD-502 plus, Spectrum technologies, Aurora, IL, USA) at five points on newly fully expanded leaves and averaged. Fruit harvesting was started when the first fruits reached marketable size through visual inspection. Fruits were weighed immediately after harvest using a sensitive weighing scale (Ohaus-Ranger 3000, R31P30, Buford, GA, USA). Crop water use efficiency was estimated as the fresh fruit weight divided by the total amount of water supplied over the period without discounting leachate volume.

4.2.6.2 Duration trial

Apart from the plant measurements described above for the interval trial, in the fertigation duration trial, measurements were taken for leaf gas exchange. Leaf gas exchange (LGE) measurements were done only in experimental run 1 at 3 weeks after transplanting. Leaf photosynthesis, stomata conductance, and transpiration were measured on newly fully expanded and the fifth leaf of each treatment using a portable infra-red gas analyzer (LI-COR 6400®, LI-COR Biosciences Lincoln NE, USA). The LGE measurements were made between the hours 09:00 to 13:00 central time (GMT-6). The leaf chamber conditions were set as follows; light level was set to 1500 µmol photosynthetically active radiation PAR m^{-2} s^{-1}, CO_2 at 400 ppm, the block temperature was set at 25 °C. A wait period of about 4 minutes was observed for stability of chamber conditions and matched before logging.

4.3 Data Analysis

Data analysis was done using the generalized mixed effects procedure (PROC GLIMMIX) in SAS software (SAS Institute, Cary, North Carolina, USA). In the fertigation interval trial, a one-way analysis of variance (ANOVA) was conducted with the intervals as fixed effect and block as random effect. In the duration trial, a two-way ANOVA of duration and experimental run was conducted for measurements taken in both runs. Posthoc mean comparison proceeded when ANOVA showed significant P-Values ($P<0.05$). Type III fixed effects means were obtained through LSMEANS function of the glimmix procedure (SAS 9.4, Cary, NC) and adjust for mean comparison was done using Tukey HSD at $\alpha=0.05$. In both fertigation interval and duration trials, data collected over time was analyzed using the repeated measures design approach. Repeated measures data were had unequally spaced timing, therefore, adjustment was done using the first order ante-dependence (ante(1)) covariance structure to correct for violations due to unequal variance. Test of polynomial orthogonal trend was conducted to establish linear or quadratic trends response variables to intervals or duration s.

4.4 Results and Discussion

4.4.1 Results of interval trial

4.4.1.1 Leachate electrical conductivity

Electrical conductivity (EC) measurement was achieved using a portal probe which measured the pH as well. The EC is an indication of the overall ionic strength of the solution and does not tell individual nutrient concentrations. A gradual increase in EC was observed from the initial to final measurement date. The EC was initially similar among the intervals, but differences began to show between intervals beginning from day 35 after transplanting (Figure 4.2). The high leachate EC observed could be due to the adjustment made to nutrient solution which resulted in overall increase in ionic composition of the fertigation solution. Also, differential uptake of water and nutrients which usually happens as the plant grows would lead to an increase in EC over time.

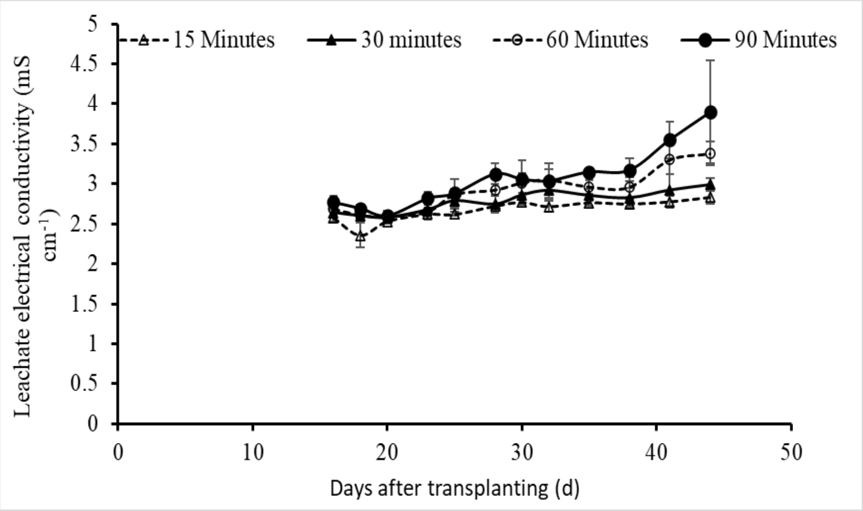

Figure 4.2. Leachate electrical conductivity (EC) for different fertigation interval sampled over various days after transplanting. Significant interaction between interval and sampling date (P=0.0007) using the repeated measures design approach, covariance structure=ante(1). Error bars are ± standard error. Measurements started 16 days after transplanting (7 days after start of fertigation treatment). All plants were maintained at 30 minutes fertigation interval prior to start of actual intervals.

4.4.1.2 Leachate Potassium and nitrate-N concentration

Intervals recording high EC also recorded high nitrate-N and potassium in the leachates (Error! Reference source not found. and Error! Reference source not found.) suggesting a positive relationship between leachate EC and measured nutrients (NO_3-N and K^+) concentration. Both nitrate-N and K^+ of leachate showed a significant quadratic response with time for each fertigation interval and begun to increase after 35 days after transplanting (DAT). Increase in leachate nutrients coincided with the peak harvesting period (5th harvest), thereby indicating a decrease in uptake as fruits are being taken. However, there was an upward adjustment in the amounts of the nutrients in the fertigated nutrient solution after the first harvest due to observed K^+ deficiency symptoms.

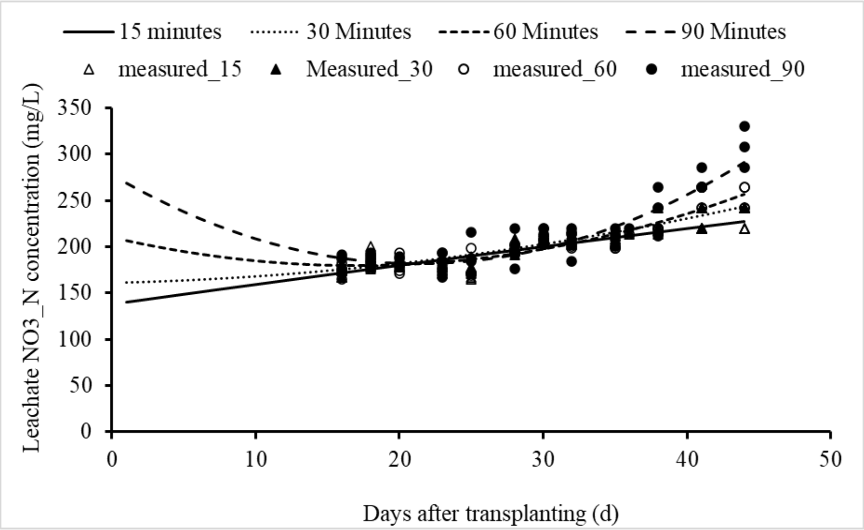

Figure 4.3. Fit for leachate nitrate nitrogen concentration (mg/L) with time (days after transplanting) for each fertigation level. Significant quadratic fits ($P<0.0001$) were observed for 60- and 90-min fertigation interval, 15- and 30-min intervals showed no significant trends ($P>0.05$) with time. Lines are fit lines and points are measured data. Lines from day 1 to 15 after transplanting are extrapolations. The Glimmix procedure was used to obtain the equation through polynomial trend analysis.

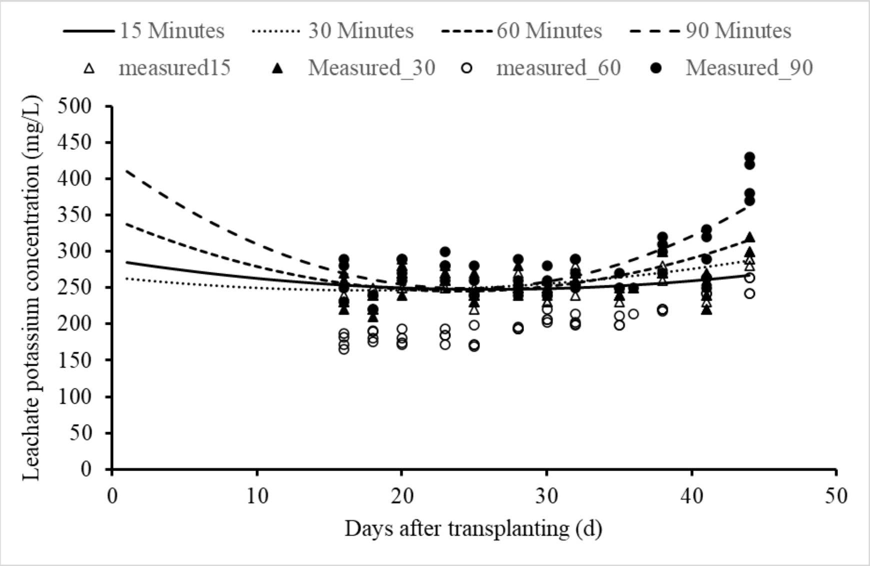

Figure 4.4. Fit for leachate potassium concentration (mg/L) with time (days after transplanting) for each fertigation level. Significant quadratic fits ($P<0.0001$) were observed for 60- and 90-min fertigation interval, 15- and 30-min intervals showed no significant trends ($P>0.05$) with time. Lines are fit lines and points are measured data. Lines from day 1 to 15 after transplanting are extrapolations. The Glimmix procedure was used to obtain the equation through trend analysis.

4.4.1.3 Leachate volume, leaching fraction and water uptake

Leachate volume corresponded with fertigation interval (Error! Reference source not found.**A**) with highest interval recording the lowest leachate volume which is indicative of the reducing amount fertigated with increasing interval. However, although leachate fraction decreased with increasing interval, there was no overarching trend in leachate fraction due to adjustment in fertigation interval (Error! Reference source not found.**B**).

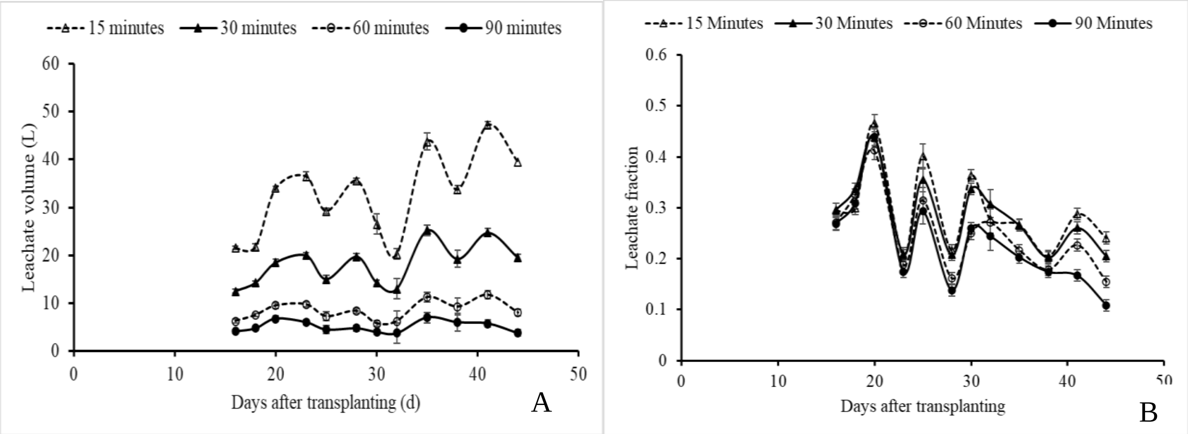

Figure 4.5. Leachate volume (A) and fraction (B) with time (days after transplanting) for each fertigation level. Error bars are two standard errors of difference of means. There was a significant interaction between interval and sampling date on leachate volume ($P<0.0001$) and leachate fraction ($P=0.0136$).

4.4.1.4 Fruit yield, water use efficiency, and biomass partitioning

Harvesting for the fertigation interval trial lasted from 25 to 49 DAT with a total of 9 harvests. Highest fruit count per square meters (53 fruits) was recorded by 90 minutes interval whilst the lowest (48 fruits) was recorded by 30 minutes with no significant difference among the intervals. Fruit yield was not also significantly different among the intervals, but lowest yield of 11.96 kg m^{-2} was recorded at 30 minutes whereas the highest yield of 13.19 kg m^{-2} was recorded by 60 minutes. The highest yields on a per plant basis (3.7 kg plant^{-1}) recorded in this study compare very wells to cucumber yields obtained in hydroponic grown cucumber with fruit thinning (Singh et al., 2019). Fruit thinning was practiced in this study as is the practice of many growers. Crop water use efficiency increased linearly with increasing fertigating interval and reached 46 kg m^{-3} at 90-minute interval. Crop water use efficiency was generally low for all fertigation intervals compared to values of up to 55.8 kg m^{-3} recorded for drip-fertigated cucumber (Wang et al., 2019) and could be due to over fertigation resulting from higher-than-expected discharge rates (**Table 4.6**). However, in season 2 of their trial, Singh et al. (2019)

obtained CWUE values similar to this study especially with fruit thinning even with 100% fertigation rate. Therefore, the values of crop water use efficiency obtained in this study coupled with the lack of significant differences among the intervals implies adopting a 90-minute interval could be ideal for the cucumber crops without yield penalties.

The dry weights, referred here as biomass, obtained from shoots, leaves, and fruits were averaged over the production period. The biomass partitioned to shoots, leaves and fruits showed similar trend as the CWUE described above. Usually, fruit biomass would be higher than shoot biomass especially since pruning of offshoots was done. However, in this study, shoot biomass was generally higher than fruit biomass due to the presence of small fruits and other side shoots that were not pruned prior biomass measurement.

Table 4.6. Effect fertigation interval on fruit yield, water use efficiency, and biomass partitioned

Fertigation interval (minutes)	Fruit count (n m^{-2})	Yield (kg m^{-2})	Crop water use efficiency (Kg m^{-3})^{z}	Biomass (g $plant^{-1}$)			
				Fruit	Leaf	Shoots	Total
15	49a*	12.16a	16.00d	13.67a	28.88a	18.88a	61.42a
30	48a	11.96a	23.59c	14.91a	30.17a	18.25a	62.42a
60	51a	13.19a	37.85b	15.85a	30.25a	18.96a	64.04a
90	53a	13.13a	46.00a	13.25a	29.58a	18.58a	61.42a
P-Value	*0.1927*	*0.3309*	*<0.0001*	*0.8933*	*0.9649*	*0.9808*	*0.9835*

^{z}Significant linear trend ($p<0.0001$) using Proc glimmix trend analysis.

*Means in columns followed by the same alphabet are not statistically different from each other ($P\geq0.05$)

4.4.1.5 Allometric relationships

Several allometric relationships were estimated for the plants as follows; plant height or vine length (cm) was divided by node count to determine internode length (cm), leaf area was divided by total aboveground plant biomass to obtain leaf area ratio (LAR, cm^2 g^{-1}), and with leaf biomass to obtain specific leaf area (SLA cm^2 g^{-1}). The leaf area index (LAI m^2 m^{-2}) was obtained by multiplying leaf area (converted to m^2 $plant^{-1}$) by number of plants per square area (n m^{-2}). These allometric relationships are useful metrics for understanding the resource allocation of the plants. It could be adduced from these allometric relationships that the fertigation interval did not affect the allocation patterns of the cucumber plants. However, the highest leaf area (LA) per plant (cm^2) was recorded by 60 minutes interval which translated into the highest LAI of 3.54 m^2 m^{-2} but the lowest LAR, 30 minutes recorded the lowest LA and thus the lowest LAI. Specific leaf area was highest at 15 minutes interval (**Table 4.7**), indicating lowest biomass per leaf area or thinner leaves. Effect of fertigation interval on SLA was dependent on date of measurement (Figure 4.6**)** which might be due to differential partitioning to optimize light use efficiency at different time points as result of light conditions. However, these differences did not translate into useful productivity as yield remained statistically the same across the intervals.

Table 4.7. Main effects of fertigation on cucumber allometric traits, leaf temperature and leaf Chlorophyll

Interval (minutes)	LA[u]	LAR[v]	Internode length[w]	Leaf temperature[x]	Leaf Chlorophyll	SLA[y]	LAI[z]
15	9757a[*]	215.4a	9.7a	26.4a	39.0a	524a	3.5a
30	9682a	217.4a	9.8a	25.5a	38.7a	513a	3.47a
60	9868a	212.2a	9.8a	25.9a	38.4a	496a	3.54a
90	9809a	219.7a	9.8a	25.9a	38.7a	518a	3.52a
P-Value[z]	*0.9858*	*0.9136*	*0.895*	*0.5214*	*0.8584*	*0.2666*	*0.9858*

[u] Leaf area per plant (cm^2 $plant^{-1}$)

[v] Leaf area ratio (cm^2 g^{-1} total above ground biomass).

[w] internode length (cm) was calculated by dividing plant height over number of nodes on the vine.

[x] Leaf temperature (°C) was measured using an infra-red thermometer

[y] SLA is specific leaf area (cm^2 g^{-1}) and

[z] LAI is leaf area index (m^2 m^{-2}); Leaf chlorophyll (SPAD Units) was measured using a portal Soil Plant Analysis Development meter (SPAD-502 plus)

[*] Means in columns followed by the same alphabet are not statistically different from each other (P≥0.05)

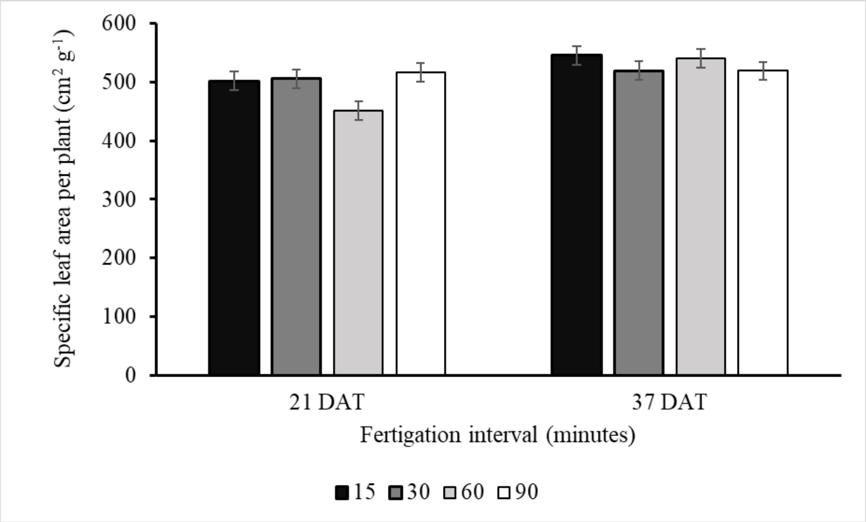

Figure 4.6. Effect of fertigation interval on specific leaf area (SLA) per plant at two dates. There was a significant interaction between fertigation interval and sampling date (P=0.0336). Intervals of 30 and 90 minutes had a slight decrease in SLA from 21 to 37 DAT whereas 15 and 60 minutes had an increase each.

4.4.1.6 Nutrients partitioned into leaves, shoots, and fruits

There was no statistically significant effect of fertigation interval on leaf nutrients content observed except for sulfur which was significantly higher at 30 minutes interval (**Table 4.8**). Also, Mn showed significantly higher levels in shoots of 15 minutes interval than the other intervals. In the fruits, only B showed difference among the intervals and was lowest at 15 minutes duration. It was observed that average tissue nitrogen (N), calcium (Ca), sulfur, and magnesium (Mg) contents across fertigation intervals was highest in leaves followed by shoot, then fruits, whereas phosphorus (P) was highest in fruit followed by leaves then shoots, average tissue potassium (K) content was highest in shoots followed by fruits then leaves. All the micronutrients followed the same partitioning pattern and were highest in leaves followed by shoots then fruits (**Table 4.9**). Patterns observed for N were expected since N is more involved in vegetative growth. Whiles K was more in shoots, Mg was more in leaves whose levels were more than twice the upper sufficiency limit (Mills and Jones Jr, 1996). Since Mg and K are competing cations (Fageria, 2001), and since Mg transport in plants is through ionophores regulation, preference was probably given to K which was then found more in the shoots (Bryson et al., 2014a). However, other transport barriers might have limited the onward transport of K into the fruits hence the observed trend. Although Mg levels in the leaves were very high which suggest luxury consumption might be taking place, results of nutrient content of water samples showed that K:Mg and Ca:Mg ratios were below optimal. Nutrient interactions do occur among K, Ca, and Mg (Fageria, 2001). These cations content of the plants depend both on their individual availability and the availability of other cations in the growth medium (Epstein, 1972) which can lead cation antagonism-a situation where excess of on cation can limit uptake of another cation but overall plant cation remains the same (Dibb and Thompson, 1985).

Tissue analysis showed that leaf sulfur was highest at 30-minute whilst fruit boron content was highest at 60-minute interval. Sulfur and boron are both anions where sulfur uptake is influenced by irrigation amount and N:S ratio of 15:1 is considered adequate for most plants (Bryson et al., 2014b). However, the estimated target N:S ratio of the fertigated solution was tremendously lower (1.6:1) indicating higher sulfur than necessary. The high sulfur content probably resulted in the observed and measured foliar K deficiency because high levels of S are known to suppress K uptake (Bryson et al., 2014b). Higher fruit boron content at 60-minute interval could be explained by need to balance ionic charge due to the higher levels of Mg, Ca and Cu assimilated into the fruits (**Table 4.8** and **Table 4.9**) which are all divalent cations.

It can be concluded from the observations made on tissue macro-and micronutrients composition that managing fertigation interval at one and half-hourly intervals resulted in similar results than other shorter intervals. Thus, for a 4-minute duration, one and half-hourly fertigation interval was adequate to meet the nutritional needs of the plants.

Table 4.8. Effects of fertigation interval on macronutrients partitioning into leaves, shoot and fruits

Interval (minutes)		Macronutrients (g 100 g^{-1})				
	N	P	K	Mg	Ca	S
	Leaf					
15	5.96a[*]	0.75a	3.10a	2.34a	4.17as	0.81ab
30	5.95a	0.77a	3.16a	2.20a	3.95a	0.85a
60	5.95a	0.78a	2.88a	2.16a	3.89a	0.77b
90	6.09a	0.80a	3.03a	2.21a	3.82a	0.78ab
P-Value	*0.5474*	*0.4891*	*0.2432*	*0.3096*	*0.3542*	*0.0231*
	Shoot					
15	4.83a	0.66a	9.20a	0.54a	1.11a	0.30a
30	4.70a	0.67a	9.11a	0.55a	1.07a	0.31a
60	4.65a	0.72a	9.22a	0.53a	1.08a	0.31a
90	4.62a	0.72a	9.09a	0.54a	1.08a	0.31a
P-Value	*0.5439*	*0.1177*	*0.8106*	*0.9079*	*0.7857*	*0.4849*
	Fruit					
15	3.90a	0.82a	4.92a	0.40a	0.35a	0.37a
30	3.95a	0.82a	4.83a	0.40a	0.34a	0.37a
60	3.95a	0.83a	4.83a	0.41a	0.37a	0.36a
90	3.93a	0.83a	4.86a	0.40a	0.35a	0.37a
P-Value	*0.9512*	*0.8225*	*0.8448*	*0.4129*	*0.1322*	*0.179*

[*] Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

Table 4.9. Effects of fertigation interval on micronutrients partitioning into leaves, shoot and fruit

Interval (minutes)	Micronutrients (mg kg^{-1})				
	Fe	Mn	Cu	B	Zn
	Leaf				
15	120.75a*	155.88a	7.00a	92.50a	35.63a
30	121.13a	151.00a	7.38a	88.00a	39.25a
60	122.38a	146.75a	8.00a	85.88a	39.63a
90	128.63a	145.88a	8.13a	88.13a	39.50a
P-Value	*0.1747*	*0.3578*	*0.1953*	*0.6203*	*0.1307*
	Shoot				
15	52.67a	47.67a	4.74a	31.13a	27.49a
30	49.65a	43.45a	4.47a	31.38a	28.51a
60	49.11a	45.34a	5.14a	31.31a	30.17a
90	49.44a	45.29a	4.75a	31.13a	28.94a
P-Value	*0.6946*	*0.8622*	*0.2903*	*0.8605*	*0.6231*
	Fruit				
15	45.00a	26.88a	3.38a	23.63b	26.38a
30	45.63a	26.38a	3.63a	24.13ab	27.25a
60	46.75a	27.63a	4.38a	25.5a	28.00a
90	48.88a	28.25a	3.88a	24.38ab	29.00a
P-Value	*0.5934*	*0.3376*	*0.3492*	*0.0348*	*0.4858*

*Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05).

4.4.2 Results of duration trial

4.4.2.1 Plant growth and leaf chlorophyll

The results (**Table 4.10**) showed that plant height (cm) in experimental run 1 was not significantly different (P>0.05) among the duration treatments. However, in experimental run 2, plant height was significantly higher in 3- than 2-minute duration at 17 days after transplanting (DAT) whereas at 25 DAT, plant height remained statistically similar among the duration treatments (P>0.05). Leaf chlorophyll content (SPAD units) was not significantly different among the duration treatments in run 1 at 21 DAT but was significantly higher for 3-minute than 1- and 4-minute durations. However, leaf chlorophyll was statistically similar between 2- and 3-minute and between 1-, 2-, and 4-minute durations (**Table 4.10**). Leaf chlorophyll values were generally low but fell within acceptable sufficiency rangesconsidered optimal for cucumber productivity (Padilla et al., 2017). However, the leaf chlorophyll values (SPAD units) recorded by fertigating for 3 minutes were close to the optimal SPAD values in cucumber. Although SPAD measurements are good predictors of the nitrogen nutrition of plants (Padilla et al., 2017), they are greatly influenced by the growth stage of the plant and when measurements are taken (Padilla et al., 2017).

Table 4.10. Effect of fertigation duration on plant height, leaf chlorophyl and node count at different sampling dates

	Plant height (cm)		Leaf chlorophyll^z		Node count	
Run 1	Days after transplanting					
Duration (minutes)	21	28	21	28	21	28
1	47.50a*	84.50a	35.48a	34.90b	8a	11a
2	62.00a	105.50a	35.85a	36.28ab	10a	13a
3	57.38a	102.25a	35.95a	39.08a	10a	12a
4	45.64a	76.25a	33.53a	34.68b	7a	11a
P-Value	*0.3374*	*0.2223*	*0.1176*	*0.0225*	*0.0535*	*0.2621*
Run 2	Days after transplanting					
Duration	17	25	17	25	17	25
1	77.38ab	128.15a	38.45a	35.18a	15a	24a
2	72.50b	120.98a	37.07a	36.90a	14a	24a
3	80.25a	131.64a	40.43a	39.05a	15a	25a
4	76.38ab	131.40a	38.3a	37.38a	14a	24a
P-Value	*0.024*	*0.1456*	*0.0613*	*0.17*	*0.1609*	*0.2614*

^{z}Leaf chlorophyll (SPAD units) was measured using a handheld Soil Plant Analysis Development meter (SPAD-502 plus)

*Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

4.4.2.2 Leaf gas exchange

Leaf gas exchange measurements were not significant among the durations tested (

Table 4.11). However, stomata conductance showed a decreasing trend with increasing duration. Leaf transpiration did not follow a similar pattern as stomata conductance indicating a poor correlation between the two. Leaf transpiration rate rather had a similar trend with leaf photosynthesis measured at photon flux density of 1500 µmol PPFD m^{-2} s^{-1} which means decreased vapor pressure deficit of the greenhouse would affect productivity of the plants. The leaf vapor pressure increased with increasing duration and decreased slightly at 4 minutes. It was expected that leaf vapor pressure deficit and transpiration rate have a positive relationship.

Table 4.11. Effect of fertigation duration on leaf gas exchange measured in Run 1.

Duration (minutes)	A_{max} (µmol [CO_2] m^{-2} s^{-1})^y	$g_{,s}$ (mmol [H_2O] m^{-2} s^{-1})^z	Leaf transpiration (mmol [H_2O] m^{-2} s^{-1})	Leaf vapor pressure deficit (kPa)
1	20.87a*	0.686a	5.44a	1.26a
2	19.27a	0.455a	4.51a	1.33a
3	20.50a	0.452a	4.87a	1.43a
4	17.72a	0.431a	4.53a	1.37a
P-Value	*0.1582*	*0.0922*	*0.2577*	*0.3235*

^{z}Stomata conductance ($g_{,s}$)
^{y}Leaf net photosynthesis rate at 1500 µmol PPFD m^{-2} s^{-1}
*Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

4.4.2.3 Yield and biomass partitioning

Yield response to fertigation duration was significantly different depending on experimental run. The higher yield of 5.12 kg $plant^{-1}$ was recorded by 2-minute duration in experimental run 1. In experimental run 2, highest yield of 3.58 kg $plant^{-1}$ was the same for plants fertigated for 1- or 4-minute duration (**Table 4.12**). Using 2-minute duration as a baseline, yield in run 1 decreased with fertigation duration whereas in run 2, yield increased with fertigation duration. The pooled results over experimental runs showed that yield decreased with increasing fertigation duration. When yield for 4-minute duration was compared with the 30-minute interval for the fertigation interval trial in which duration was also maintained at 4 minutes, it was observed that on average, yield in the duration trial was 6% more than in the fertigation interval trial indicating a general improvement in performance. Hydroponic fertigated cucumber obtained yields of between 2.4 -3.6 kg plant^{-1} with fruit thinning (Singh et al., 2019) which means, the results obtained in this study compares well with the yields obtained in the literature. The observations indicate that if a higher fertigation frequency of 30-minute interval is to be used, then fertigation duration could be reduced to 1 minute without significant yield penalties.

Table 4.12. Effect of fertigation duration on yield and biomass partitioning, fixed effects, and random/covariance estimates

	Yield (kg plant^{-1})^{w}		Biomass (g plant^{-1})					
			Fruits^{y}		Leaves^{x}	Shoot^{x}	Total^{y}	
Duration (minutes)	Run 1	Run 2	Run 1	Run 2	Pooled	Pooled	Run 1	Run 2
1	4.71a	3.58a	161.52ab	128.61a	62.31a	23.12a	246.24ab	216.03a
2	5.12a	3.10a	227.51a	116.3a	61.89a	23.58a	316.11a	195.72a
3	4.52ab	3.52a	186.97ab	142.06a	69.43a	21.66a	265.48ab	248.65a
4	3.49b	3.58a	108.53b	140.64a	50.89a	16.82a	159.39b	222.28a
P-Value	*0.0041*	*0.3591*	*0.0125*	*0.1942*	*0.279*	*0.066*	*0.0253*	*0.4546*
Experimental Run								
Run1	4.46a		171.13a		50.66b	25.22a	246.81a	
Run2	3.45b		131.90b		71.6a	17.37b	220.64a	
P-Value	*<.0001*		*0.0011*		*0.001*	*0.0003*	*0.1028*	

^{z}EU=experimental unit

*Means in columns followed by the same alphabet are not statistical different (P≥0.05)

^{y} Effect of fertigation duration on fruit and total biomass depended on experimental run (P= 0.001 and P=0.0051 respectively). Therefore, only the simple effects are presented for fruit and total biomass.

^{x}There was no significant interaction effect of duration and experimental run on leaves and shoot biomass, P=0.16 and P=0.0852 respectively. Therefore, only the main effects of duration on leaves and shoot biomass are presented.

^{w}There was no significant interaction effect of duration and experimental run on fruit yield (P=0.01). Therefore, the simple effects of duration for each experimental run on yield are presented

4.4.2.4 Plant macronutrient uptake

There were no significant effects (P>0.05) of the fertigation duration treatments on macronutrients content of total aboveground tissue (**Table 4.13**). However, comparing the macronutrient content of the duration trial to the 4-minute duration of the 30-minute interval in the interval trial (section **4.4.1.6**), the macronutrient content of the plant tissue N, P, K, Mg, Ca, and S was 10, 54, 31, 103, and 26% higher respectively higher. This means the plants generally had better macronutrient uptake in the duration trial than in the interval trial and could be attributed to differences in the weather condition of the two trials. Apart from tissue nitrogen whose content was lowest at 1-minute duration, the results show that fertigating for 1 minute effective at maintaining good tissue macronutrients content.

Table 4.13. Effect of fertigation duration total macronutrients per plant in experimental run 1

Duration (minutes)	Macronutrients (g 100 g^{-1}) N	P	K	Mg	Ca	S
1	14.71a[*]	3.93a	22.63a	6.43a	11.29a	2.22a
2	15.75a	3.72a	21.92a	6.37a	12.41a	1.95a
3	16.21a	3.56a	22.27a	7.21a	10.87a	1.95a
4	16.10a	3.48a	22.35a	6.84a	10.89a	1.93a
P-Value	*0.0724*	*0.1771*	*0.9176*	*0.6617*	*0.2824*	*0.0809*

[*] Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

4.4.2.5 Plant micronutrients uptake

The effect of fertigation duration on micronutrients in total aboveground plant tissue are presented in **Table 4.14**. The results show that tissue manganese (Mn) and zinc (Zn) contents were not statistically influenced by fertigation duration (P>0.05). However, fertigation duration scheduling resulted in significant differences in tissue iron (Fe) copper (Cu) and boron (B) contents (**Table 4.14**). For tissue Fe content, 1-, 2- and 3-minutes were statistically similar (P>0.05). Also, 1-, 2-, and 4-minute duration were statistically similar whilst 3- minute duration had significantly higher (P<0.05) tissue Fe content than 4-minutes duration. Tissue Cu content was significantly higher in 1-minute than in 3-minute duration. However, there were no statistical difference between 1-, 2-, and 4- minute and between 2-, 3-, and 4-minute durations on tissue Cu content. Maximum tissue B content was recorded at 3-minute duration followed by 4-minutes. However, tissue B content was not statistically different between 2-, 3- and 4-minute and between 1-and 2-minute duration. The trends show that duration effect on tissue micronutrients was probably based on need to balance the ionic charge of the plants. Thus, durations that already led to high assimilation of certain cations would also lead to assimilation of the complementary anions to balance the overall charge of the plants. For instance, the highest Fe, and lowest Cu (both divalent cations) assimilation occurring at 3-minute duration was coupled with the highest B, and a relatively low P and N. Also, the lowest B was recorded at 1 minute duration and coincided with highest P. Therefore, by adjusting fertigation duration, uptake was naturally adjusted to obtain the right ionic balance required for optimal performance of the plants. Ultimately, choice of a particular fertigation duration would not affect the overall nutrition of the plants albeit differences would exist in uptake of different elements.

Table 4.14. Effect of fertigation duration on total micronutrients content per plant in experimental run 1

	Micronutrients (mg kg^{-1})				
Duration (minutes)	Fe	Mn	Cu	B	Zn
1	274.75ab[*]	496.75a	33.25a	209.00b	190.75a
2	281.50ab	520.25a	29.00ab	276.25ab	176.50a
3	294.25a	602.00a	27.25b	323.50a	184.00a
4	264.25b	487.00a	29.00ab	281.00a	178.75a
P-Value	0.0121	0.0488	0.0441	0.0028	0.9036

[*] Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

4.5 Conclusion

Fertigation interval and duration experiments were conducted using hydroponic nutrient solution. In the first trial, the aim was to identify appropriate fertigation interval at a 4-minute duration. In the second trial conducted in two sets of experimental runs, the aim was to identify optimal duration levels for a half-hourly fertigation interval. It was observed that apart from leaf sulfur content which was highest at 30-minute interval and lowest at 60-minute interval, tissues macronutrients content partitioned in leaves, shoots, and fruits remained the same across fertigation intervals. Therefore, irrespective of fertigation interval, more micronutrients were partitioned into leaves than shoots, and shoots than fruits. Partitioning of macronutrients into tissue parts depended on the nutrient element such that similar partitioning patterns were observed for nitrogen (N), calcium (Ca), sulfur, and magnesium (Mg) contents and different patterns for phosphorus (P), and potassium (K). Also, fertigation interval failed to significantly influence cucumber growth and yield whereas water use efficiency significantly increased with increasing fertigation interval. Therefore, due to the increased crop water use efficiency and linear reduction in leachate volume with increasing intervals, fertigating every 90 minutes for the 4-minute durations was identified as the most efficient fertigation interval.

Results from fertigation duration trial at a half-hourly interval showed no effect on total aboveground tissue macronutrients content. However, fertigation duration influenced tissue iron (Fe) copper (Cu) and boron (B) contents and promoted highest tissue Fe and B at 3 minutes duration whereas highest tissue Cu content was recorded at 1 minute duration. Thus, by adjusting fertigation duration, uptake was naturally adjusted to obtain the right ionic balance required for optimal performance of the plants. Therefore, choice of a particular fertigation duration would not affect the overall nutrition of the plants albeit differences would exist in uptake of different elements. Yield response to fertigation duration was significantly different depending on experimental run. The highest yield of 5.12 kg plant^{-1} was recorded at 2-minute duration in experimental run 1 whereas highest yield of 3.58 kg plant^{-1} was recorded at 1- or 4-minute duration in experimental run 2. The observations indicate that if a higher fertigation frequency of 30-minute interval is to be used, then fertigation duration could be reduced to 1 minute without significant yield penalties.

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Chapter V

Growth and yield response of cucumber to fertigation duration using biofloc aquaculture effluent with and without supplementation.

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Abstract

Fertigation management is a practical solution to reducing leachate and increasing nutrients and water use efficiency in drain-to-waste systems. Although nutrient concentration of aquaculture effluent (AE) can be proved through nutrient supplementation, optimal fertigation management is still required to reduce wastage. Therefore, experiments were conducted aimed at determining optimum fertigation duration in soilless cucumber, grown using aquaculture effluent (AE), with or without nutrient supplementation. The experiments were arranged in a split plot nested in the randomized complete block design with four replications. The main-plot factor was fertigation duration at 1, 2, 3, or 4 minutes and the subplot factor was nutrient solution type, supplemented or sole AE. Fertigation interval was maintained at every 30 minutes. The results showed that fertigation duration was ineffective at influencing growth parameters, leaf gas exchange measurements. Fertigating for only 1-minute duration resulted in significant yield reduction whereas fertigating for 3 minutes generally promoted higher yields and total aboveground biomass but was not statistically far from yields obtained by fertigating for 1 minute. The effect of fertigation duration on fruit, and shoot biomass depended on experimental runs which were governed by differences in the greenhouse microclimate. Comparing supplemented and sole AE, only a 7% higher yield was obtained due to nutrient supplementation and is considered inadequate to warrant need for nutrient supplementation. Therefore, under the current condition, use of sole AE is adequate to obtain desirable yields in cucumber production. Results of tissue macro- and micronutrients as well as leachate nitrate-N and electrical conductivity further suggest that nutrients supplied by sole AE was adequate to support the performance of the plants and nutrient supplementation was not justifiable. The results from this study would be useful when sizing a decoupled aquaponics system in deciding which fertigation duration to adopt. The results are also useful for aquaponics farmers who adopts drain-to-waste approach in managing aquaculture effluent.

Keywords: aquaponics, nutrient use efficiency, nutrient management, timer clock, nutrient uptake, leachate

5.1 Introduction

The integrated combination of aquaculture and horticulture also known as aquaponics was introduced to ameliorate environmental pollution by aquaculture waste and is considered a sustainable approach to food production (Konig et al., 2016; Nehar, 2013; Tyson et al., 2012). The system is also considered a water and nutrient efficient system as it characteristically recycles resources such as aquaculture waste (Nichols and Savidov, 2012). However, the extent of resource use efficiency especially as it pertains to nutrients and water use is contingent on aquaponics system type. Decoupled aquaponics systems have been shown to have advantages over coupled systems (Goddek et al., 2016). However, the advantages of decoupled aquaponics diminishes with challenges of water and nutrients use (Goddek, 2017).

Attempts have been made to increase availability of nutrients through mineralization of the sludge (Goddek et al., 2018) and nutrient supplementation (Delaide et al., 2016). With leafy vegetables, reports show that aquaponics systems can meet crop nutrient demands with or without supplementation (Delaide et al., 2016; Pinho et al., 2018, 2017). The few studies that examined fruit vegetables grown in aquaponics systems indicate promising performance of these crops even without nutrient supplementation and mostly attributed to presence of solids (Blanchard et al., 2020; Knaus and Palm, 2017). In conventional hydroponic systems, fertigation management has contributed to meeting crop water and nutrient needs whilst safeguarding the environment (Kumar et al., 2018; Liang et al., 2014; Papadopoulos, 2001; Singh et al., 2018; Wang et al., 2019). Therefore, as most aquaponics practitioners navigate towards decoupled or multi-loop systems (Goddek et al., 2016), there is need to assess fertigation management as a tool for efficient aquaculture effluent use.

Fertigation management is a more practical approach to managing aquaculture effluent in decoupled aquaponics than coupled systems due to the non-recirculating nature of the former. This is because, in decoupled systems, water is not only lost via evapotranspiration, but also through drainage. The extent of drained water to the environment is dependent on characteristics of the growing medium, plant growth, water uptake versus supply. Due to the low nutrient concentration of aquaculture effluent (Bittsánszky et al., 2016) there is a temptation to fertigate more than the growing medium can hold. One of the most frequently substrates used in soilless vegetable production is perlite which falls in the category of granular substrates with poor water holding capacity of between 10 and 40 % v/v (Maher et al., 2008). High free drainage in such porous substrate requires increasing fertigation frequency but reducing duration at each irrigation so that drainage is at acceptable limits. Studies show that shorter duration irrigation intervals are better at saving water and increasing cucumber yields than the longer intervals (Wang et al., 2019). Therefore, optimizing fertigation duration is essential to reducing drainage and leaching in our drain-waste system which hitherto would affect nutrient and water use efficiency (Dasgan et al., 2012) as well as pose environmental concerns. The aim of this study was to provide optimum fertigation duration at half-hourly interval for cucumber fertigated with aquaculture effluent with and without nutrient supplementation.

5.2 Materials and Methods

5.2.1 Plant cultivation

The trial was conducted in a double-layered plastic-covered greenhouse at Auburn University E.W. Shell fisheries station, aquaponics project site. There were two experimental runs lasting from 1/22/2021 to 4/15/2021 and 4/13/2021 to 6/16/2021 for run 1 and run 2, respectively. Cucumber (*Cucumis sativus* L. 'Delta star') seeds were raised in 72-count round (58 mL) cells styrofoam seeding trays (Hydrofarm, Pentaluna, CA) filled with commercial germination potting mix (Miracle-Gro®, The Scotts LLC, CA, USA). Trays were placed under greenhouse conditions and watered to keep media moist. Three-week old uniformly strong seedlings were transplanted into 11-L rectangular Dutch buckets (Crop King Inc., Lodi, Ohio) filled with 100% horticultural grade perlite media, single plant per pot maintained at a density of 3.6 plants m^{-2} (0.30 m × 0.91 m). All plants were trained to one stem per plant by pruning all lateral growth and were vertically trellised using plastic clips (Bato bobbins, Crop King, Lodi, Ohio) along a twine that was attached to a horizontal cable suspended about 4 m above ground level to serve as support. The first four fruits from the base of the plant were removed to encourage early vegetative growth. Starting at the fifth node, fruits were allowed to reach maturity and were harvested three times per week. All foliage including and below the third node below the oldest fruit was removed regularly.

5.2.2 Treatments and experimental design

Treatments were a combination of fertigation duration (4 levels) and nutrient solution type (2 levels), resulting in a total of 8 treatment combinations. Fertigation interval was maintained at every 30 minutes. Fertigation durations were 1, 2, 3, or 4, and the nutrient solution types were sole or supplemented aquaculture effluent. Nutrient supplementation was achieved with a 1:100 fixed-ratio chemilizer injector (QC Supply, Schuyler, NE, USA) used to inject formulated stock solution to AE (**Figure 5.1**). The fertigation volume for each nutrient solution type at the different durations is presented in **Table 5.1**. Stock solution for nutrient supplementation was made as half the rate of the hydroponics complete fertilizer (N-P-K 5-12-26), Magnesium sulfate (10% Mg, 13% S), and potassium nitrate (13-0-46 N-P-K) to supply 90, 31.5, 150, 75.5, 32.5 mg L^{-1} of N, P, K, Ca, Mg, and S respectively in run 1 (**Table 5.2**). The mid-season analysis of the macro-and micro-nutrients from each nutrient solution type are presented in **Table 5.3** and **Table 5.4**. Samples of fertigation solution were collected and measured for EC, pH and nitrate N and have been averaged on weekly basis **Table 5.5**.

The experiments were laid in a split plot with fertigation duration as the main-plot factor, nested in RCBD, and nutrient solution type was the sub-plot factor.

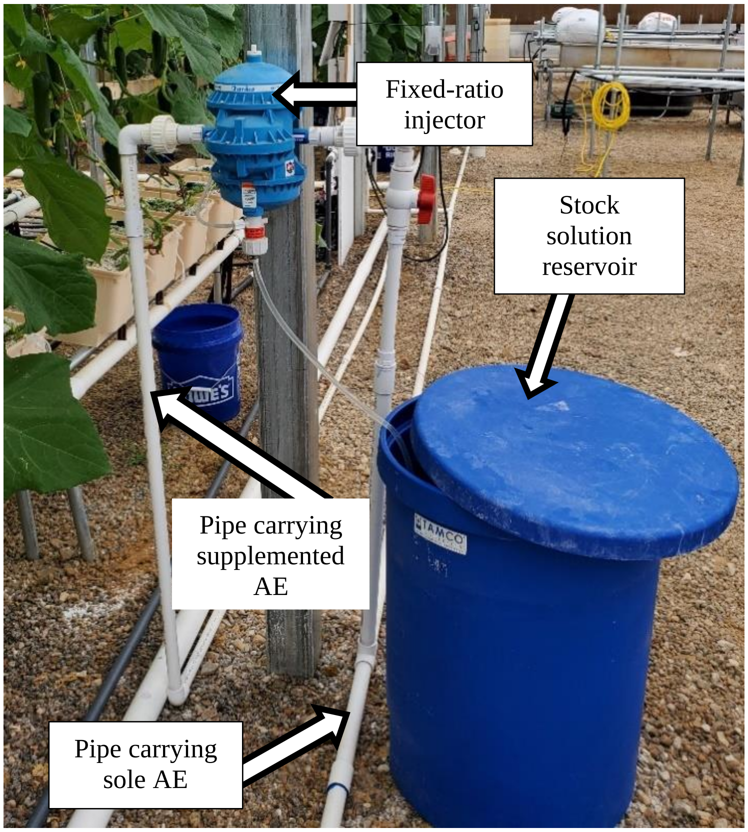

Figure 5.1. Fixed-ratio injection system used for nutrient supplementation.

Table 5.1. Estimated daily fertigation volume for each duration for sole and supplemented aquaculture effluent (AE)

Duration	discharge (L h^{-1})		Volume (L plant^{-1} d^{-1})	
(Minutes)	Sole AE	Supplemented AE	Sole AE	Supplemented AE
1	7.4	8.3	3.0	3.3
2	5.7	4.4	4.6	3.5
3	4.4	4.6	5.3	5.6
4	4.3	4.8	6.8	7.7

Table 5.2. Target nutrient concentration used in supplementation. The set 1 and set 2 were adjustments at different stages of the plant growth

	Target concentration (mg L^{-1})		
	Run1		
Nutrient	set 1	set 2	Run 2
NO3-N	73.86	96.02	25.00
Phosphorus (P)	103.18	134.13	26.22
Potassium (K)	255.80	332.54	107.90
Magnesium (Mg)	131.07	170.40	45.00
Sulfate (S)	169.50	220.35	60.27
Iron (Fe)	3.00	3.90	1.50
Manganese (Mn)	0.50	0.65	0.25
Zinc (Zn)	0.15	0.20	0.08
Molybdenum (Mo)	0.19	0.25	0.10
Copper (Cu)	0.15	0.20	0.08
Boron (B)	0.50	0.65	0.25

Table 5.3. Mid-season analysis of water macronutrients of sole and supplemented aquaculture effluent (AE), run 1

	Nutrient concentration (mg L^{-1})						
Nutrient solution type	NO3-N	NH4-N	P	K	Ca	Mg	Sulfate-S
Sole AE	109.11	0.18	12.09	229.42	115.44	13.36	34.91
Supplemented AE	131.42	0.09	29.77	305.57	118.21	44.86	152.15

Table 5.4. Mid-season analysis of water micronutrients of sole and supplement aquaculture effluent (AE) in experimental run 1.

Nutrient solution type	Nutrient concentration (mg L-1)				
	B (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
Sole AE	0.073	0.01	0.048	0.035	0.02
Supplemented AE	0.210	0.01	0.268	0.85	0.065

Table 5.5. Measured EC, pH, NO_3-N and K^+ of aquaculture effluent (AE) from clarifier and fish tank during experimental run 1

	EC (mS cm^{-1})		pH		NO3-N (mg L^{-1})		K+ (mg L^{-1})	
DAT	Clarifier	Fish Tank	Clarifier	Fish Tank	Clarifier	Fish Tank	Clarifier	Fish Tank
9	1.27	1.33	5.7	5.2		.		
11	1.29		5.8		70.4	.		
14	1.22	1.24	5.2	5.2	72.6	79.2		
17	1.24	1.27	6.7	6.5	103.4	99.0		
19	1.25	1.27	6.9	6.6	110.0	103.4		
21	1.34	1.34	6.8	6.5	74.8	70.4		
23	1.29	1.36	6.8	6.5	105.6	94.6		
25	1.13	1.48	6.7	6.7	77.0	81.4		
38	1.57	1.53	7.4	7.2	90.2	94.6	190	190
39	1.68	1.68	7	7.0	99.0	99.0	280	280
42	1.56	1.57	6.7	6.5	105.6	103.4	240	250
48	1.57	1.6	7.1	6.8	96.8	85.8	270	210
52	1.65	1.73	6.9	6.7	92.4	88.0	310	330
57	1.43	1.49	6.3	6.1	90.2	88.0	210	230
61	1.4	1.35	7.0	7.0	121.0	96.8	240	220

5.2.4 Measurements of plant traits

Plant height was measured from substrate level (base of the plant) to the apical meristem using a meter rule. Number of nodes were determined by counting nodes on the main stem starting from the lowest node to the top of the most apparent node through visual assessment. Samples of leaves, stems, and fruits were taken to determine tissue elemental contents. Leaf samples were oven dried at 105 °C for 48 h whilst fruit samples were dried for up to 1 week.

Tissue analysis of plant parts for macro-and micronutrients was a using Inductively Coupled Plasma-Emission Spectroscopy (ICP_ES) via the AOAC official method 985.01 (AOAC, 2012) at Waters Agricultural Laboratory in Camilla, Georgia. In the fertigation interval trial, leaf area was measured from leaves sampled for nutrient analysis using a leaf area meter (LI-COR 3100®, LI-COR Biosciences Lincoln NE, USA). Specific leaf area ($cm^2\ g^{-1}$) per pot was calculated by dividing leaf area (cm^2) over leaf dry weight (g). Leaf chlorophyll was measured with a portable Soil Plant Analysis Development meter (SPAD-502 plus, Spectrum technologies, Aurora, IL, USA) at five points on newly fully expanded leaves and averaged. Fruit harvesting was started when the first fruits reached marketable size through visual inspection. Fruits were weighed immediately after harvest using a sensitive weighing scale (Ohaus-Ranger 3000, R31P30, Buford, GA, USA). Leaf gas exchange (LGE) measurements were done only in experimental run 1 at 3 weeks after transplanting. Leaf photosynthesis, stomata conductance, and transpiration were measured on newly fully expanded and the fifth leaf of each treatment using a portable infra-red gas analyzer (LI-COR 6400®, LI-COR Biosciences Lincoln NE, USA). The LGE measurements were made between the hours 09:00 to 13:00 central time (GMT-6). The leaf chamber conditions were set as follows; light level was set to 1500 µmol photosynthetically active radiation PAR $m^{-2}\ s^{-1}$, CO_2 at 400 ppm, the block temperature was set at 25 °C. A wait period of about 4 minutes was observed for stability of chamber conditions and matched before logging.

5.3 Data analysis.

A two-way analysis of variance (ANOVA) of fertigation duration by nutrient solution type was conducted using proc glimmix in SAS (SAS Institute, Cary, North Carolina, USA). For growth parameters measured over different sampling dates on the same plant, the repeated measures design ANOVA was used to account for autocorrelation. The covariance structure type ante(1) was adopted for repeated measures due to unequally spaced sampling dates. Where data existed for the two experimental runs, a three-way ANOVA of duration by nutrient solution type by experimental run was conducted. In all analysis approaches, block was considered a random variable and for yield measured on individual plants, plant indicated by pot was also considered a random variable. The posthoc mean separation was done where ANOVA showed significant F-probability ($P<0.05$) using lsmeans function in SAS with the Tukey HSD procedure. When the two- or three-way interaction was significant ($P<0.05$), simple effects were presented.

5.4 Results and discussion

5.4.1 Fertigation solution electrical conductivity, pH, NO_3-N concentration, and volume

Low aquaculture effluent (AE) nutrient concentration is a general problem of many aquaponics systems (Bittsánszky et al., 2016) and it is shown here that the AE used in this current study was not an exception. The AE data fertigated to the plants during run 1 are presented in **Table 5.6**. The fertigated solution pH of sole and supplemented AE ranged from 5.5 to 7.5 and 5.4 to 7.2, respectively. Many studies have attempted both successfully (Tyson et al., 2008, 2007; Zou et al., 2016) and unsuccessfully (Tyson et al., 2008, 2007; Zou et al., 2016) to lower the higher AE pH aimed at improving nutrient availability and uptake of plants grown in aquaponics. The pH range of the sole AE observed in this study could be considered an albeit not an ideal range for plant nutrients availability. The electrical conductivity measures the overall ionic strength of the nutrient solution and was shown to range from 1.2 mS cm^{-1} to 2.0 mS cm^{-1} for sole and 1.4 mS cm^{-1} to 2.2 mS cm^{-1} for supplemented AE. and nitrate N levels ranged from 69.3 mg L^{-1} to 100.7 mg L^{-1}, and 91.3 mg L^{-1} to 146.3 mg L^{-1} respectively for sole and supplemented AE. Nutrient supplementation effectively increased the average influent EC to the plants by 37% and average nitrate N by 29%.

Table 5.6. Sampled measurements of emitter solution electrical conductivity (EC), pH, and nitrate-N for each nutrient Solution type during run 1at different days after transplanting (DAT).

DAT	Supplemented AE^z			Sole AE		
	EC (mS cm^{-1})	pH	NO_3-N (mg L^{-1})	EC (mS cm^{-1})	pH	NO_3-N (mg L^{-1})
11	1.8	5.5	99.6	1.4	5.5	78.7
14	2.2	5.4	112.8	1.2	5.5	74.3
17	2.2	5.7	146.3	1.3	6.0	99.6
19	2.2	6.3	131.5	1.3	6.8	95.7
21	2.2	6.4	91.3	1.3	6.9	69.3
23	1.5	7.0	104.5	2.0	6.7	95.7
25	1.4	6.9	110.6	1.3	6.9	95.7
38	2.0	7.2	120.5	1.5	7.5	100.7

^{z}AE=Aquaculture effluent

5.4.2 Leachate electrical conductivity, pH, NO3-N, and volume

Measured leachate data (**Table 5.7**) showed that plants fertigated with supplemented AE leached out on average 56% EC and 41% more nitrate N than those fertigated with sole AE. The leachate pH of sole and supplemented AE remained closely similar during the growth period. Leachate volume increased with increasing fertigation duration and showed anticipated trends. Total leachate volume showed little difference between 2- and 3-minute durations (**Figure 5.2**) with an average of 11% compared with the estimated daily fertigation volume difference of 38% between the two durations. Estimated daily leachate volume were 0.86, 1.54, 1.71, and 3.62 L plant^{-1} day^{-1} with leachate fractions of 27.4%, 38.03%, 31.19%, 49.9% respectively for 1-, 2-, 3-, and 4-minute duration. It is not known why 2-minute duration resulted in higher leachate fraction than 3-minute duration. However, inaccuracies in leachate volume estimation might account for higher leachate fraction of 2-minute duration. The leachate information implies that supplementing the aquaculture effluent only leads to an increased amount of leached nutrients especially since leachate volume increased with fertigation duration (**Figure 5.2**). This is because, cucumber has a low nutrient extraction rate (Graber and Junge, 2009) which means excess application would accumulate in the leachate.

Table 5.7. Measured leachate EC, pH, and NO3-N concentration during run 1 at different days after transplanting (DAT). Datapoints are averaged over fertigation durations

	EC (mS cm^{-1})		pH		NO_3-N (mg L^{-1})	
DAT	Supplemented AE^z	sole AE	Supplemented AE	sole AE	Supplemented AE	sole AE
11	1.95	1.42	5.3	5.2	104.0	80.2
14	1.82	1.41	5.2	5.3	104.3	86.2
17	2.14	1.31	5.3	5.3	146.6	105.3
19	2.13	1.31	5.9	6.0	148.0	102.0
21	2.36	1.34	6.2	6.5	131.5	83.0
23	1.85	1.32	6.7	6.8	124.2	104.6
25	1.51	1.22	6.8	6.9	129.0	118.5
28	2.00	1.13	6.9	6.9	117.6	82.0
31	2.36	1.46	7.2	7.2	93.3	47.6
36	2.42	1.45	6.7	6.9	114.5	65.6
39	2.44	1.42	7.1	7.0	94.9	54.7

^{z}AE=Aquaculture effluent

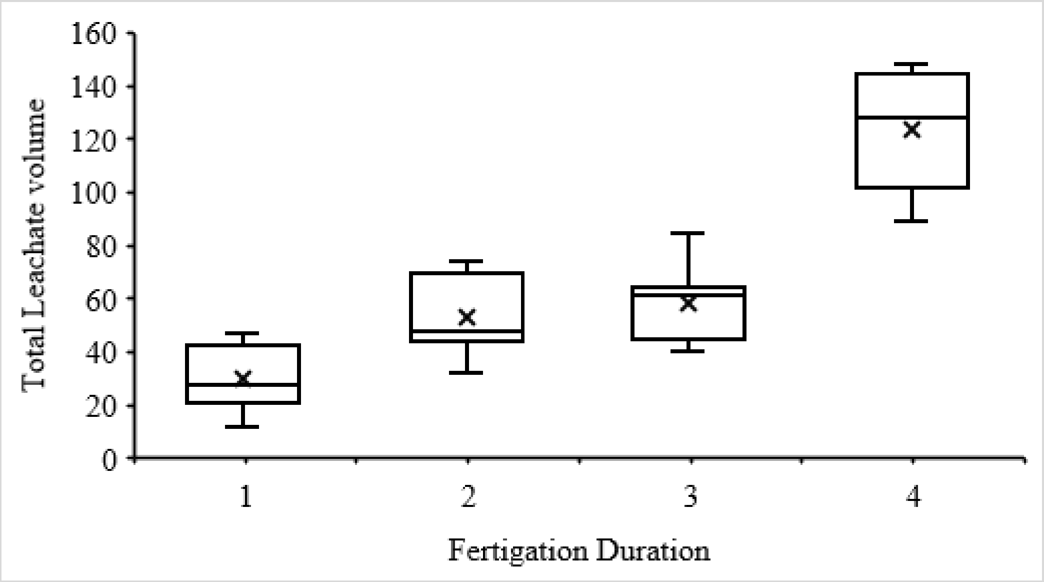

Figure 5.2. Total leachate volume in liters, collected from day 27 to 61 after transplanting in run 1, averaged over nutrient solution type. Minimum volume the container measure accurately was 2 liters, therefore, volumes less than 2 liters were not considered.

5.4.3 Growth, and leaf gas exchange

The growth parameters measured were plant height or vine length (cm), node count and general leaf chlorophyll (SPAD units). Leaf chlorophyll measured using Soil Plant Analysis Development (SPAD) approach is a proxy assessment of the nitrogen status of the plant because the two traits correlate with each other (Padilla et al., 2017). There was significantly higher SPAD value recorded for plants fertigated with supplemented aquaculture effluent (AE) than the sole AE across both experimental runs (**Table 5.8**). However, the effect of nutrient supplementation on leaf SPAD was only increased by 6% over the sole indicating no significant horticultural significant effect. Therefore, it can be adduced that both nutrient types promoted overall nutritional health of the cucumber plants similarly.

The height and node count of the plants were not statistically influenced by nutrient solution type. This means growth remained similar for both nutrient solution types. However, the effect of fertigation duration on plant height and node count depended on experimental run. Fertigation duration had no significant effect (P>0.05) on growth, leaf gas exchange, and yield of the plants. Also, there was no significant effect of nutrient solution type on leaf gas exchange parameters (**Table 5.9**).

Table 5.8. Simple effects of duration and of nutrient solution type on leaf chlorophyll, Height and Node Count at each experimental run.

Duration	SPAD		Height		Node Count	
minutes	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
1	34.78a*	32.60a	76.94a	119.13b	10.25a	22.88b
2	35.34a	31.35a	84.05a	133.18a	10.95a	25.00a
3	36.30a	30.94a	100.12a	130.18ab	12.63a	24.75a
4	35.65a	32.19a	88.31a	130.85ab	11.63a	24.88a
P-Value	*0.5571*	*0.1541*	*0.2158*	*0.0245*	*0.1463a*	*0.0035*
Nutrient solution type						
Sole AE^y	34.84b	30.55b	86.75a	126.24a	11.31a	24.06a
supplemented AE	36.19a	32.99a	87.96a	130.43a	11.41a	24.69a
P-Value	*0.0343*	*0.0002*	*0.8858*	*0.2093*	*0.8834*	*0.0544*

*Means in the same column followed by the same alphabet are not statistically different (P≥0.05)
^{y}AE=Aquaculture effluent

Table 5.9. Main effects of duration and of nutrient solution type on leaf gas exchange parameters

Duration (minutes)	Amax (mol [CO_2] m^{-2} s^{-1})	$g_{,s}$ (mmol [H2O] m^{-2} s^{-1})	Leaf Transpiration (mmol [H_2O] m^{-2} s^{-1})	leaf vapor pressure deficit (kPa)
1	20.63a*	0.65a	5.51a	1.29ns
2	20.32a	0.59a	5.29a	1.26
3	20.53a	0.55a	5.26a	1.38
4	19.17a	0.48a	4.71a	1.33
P-Value	*0.2658*	*0.1512*	*0.0646*	*0.6064*
Nutrient solution type				
Sole AE^y	19.94ns	0.58a	5.14a	1.29a
supplemented AE	20.38	0.56a	5.25a	1.34a
P-Value	*0.444*	*0.7181*	*0.5886*	*0.1874*

*Means in the same column followed by the same alphabet are not statistically different (P≥0.05)
^{y}AE=Aquaculture effluent

5.4.4 Total aboveground tissues nutrients content and uptake use efficiency

The results on total aboveground tissue nutrient content and uptake use efficiency are presented for only run 1. The results showed that fertigation duration and its interaction with nutrient solution type had no significant ($P>0.05$) effect on total aboveground tissue macronutrients content except calcium (Ca). The effect of fertigation duration on tissue Ca content was independent of nutrient solution type and was significantly lower at 1-minute than 2-minute fertigation duration (**Table 5.10**). The results of tissue micronutrients (**Table 5.11**) showed that effect of fertigation duration on total aboveground tissue zinc (Zn) content depended on nutrient solution type. The tissue Zn content of plants fertigated with sole AE was significantly lowest at 1-minute duration whereas for plants fertigated with supplemented AE, fertigation duration had no significant effect on tissue Zn content. The effect of fertigation duration on tissue copper (Cu) content was independent of nutrient solution type. Fertigation for 1 minute resulted in significantly lower tissue Cu content than the other duration levels (**Table 5.11**). There were no statistically significant effects of fertigation duration or its interaction with nutrient solution type on tissue iron (Fe), manganese (Mn), and boron (B) contents. Nutrient supplementation led to a significantly higher tissue contents of phosphorus (P), potassium (K), Magnesium (Mg), sulfur (S), Mn, and Cu but lower uptake of Ca, and Zn than the sole AE. Nutrient supplementation also led to a significantly lower nutrient uptake use efficiency of P, Mg, and S than sole AE (**Table 5.12**). Generally, fertigation duration had no statistically significant main effects on uptake use efficiency of macronutrients (**Table 5.12**).

Tissue nutrient content represents uptake and is influenced by the growing environment, substrate characteristics, nutrient and water supply, and plant growth stage. Since the growing environmental conditions were generally uniform across all the treatments, differences in uptake can be attributed to the supply, in terms of fertigation duration and nutrient solution type. For macronutrients, the trends suggest that nutrient supply due to fertigation duration was adequate across all duration levels. However, nutrient solution type did play a role in nutrient uptake. Interestingly, although nitrate supply was higher in the supplemented than sole AE (**Table 5.6**), its uptake remained similar for both nutrient solution types (**Table 5.10**). The similarity of nitrogen uptake irrespective of supply could be attributed to the high mobility of nitrogen especially in porous substrates such as perlite which makes it easily leach out (Groenveld et al., 2019). This observation is supported by the higher leachate nitrate-N due to nutrient supplementation (**Table 5.7**). Also, because cucumber has lower extraction rate of nitrogen (Graber and Junge, 2009), supplementation does not necessarily lead to enhanced uptake.

Table 5.10. Macronutrients' content of total aboveground dry matter in run 1

Duration (minutes)	N	P	K	Mg	Ca	S
1	12.72a*	2.89a	22.01a	3.91a	14.28b	1.83a
2	13.17a	3.20a	22.34a	3.45a	17.14a	2.05a
3	13.30a	3.28a	22.29a	3.30a	16.65ab	1.97a
4	13.64a	3.53a	23.23a	3.50a	16.6ab	2.22a
P-Value	*0.6248*	*0.0623*	*0.4736*	*0.7532*	*0.0172*	*0.0602*
Nutrient solution type						
Sole AE[y]	12.88a	2.72b	22.11b	2.37b	17.68a	1.66b
Supplemented AE	13.53a	3.73a	22.83a	4.71a	14.65b	2.39a
P-Value	*0.0782*	*<0.0001*	*0.0422*	*<0.0001*	*0.0001*	*<0.0001*

*Means in the same column followed by the same alphabet are not statistically different from each other (P≥0.05)

[y] AE=Aquaculture effluent

Table 5.11. Micronutrients' content of total aboveground dry matter in run 1

Duration					Zn[z]	
	Fe	Mn	Cu	B	Sole AE	Supplemented AE
1	238.37a	346.50a	33.63b	165.00a	234.75b	233.50a
2	275.25a	377.88a	39.13a	159.75a	378.75a	245.50a
3	246.00a	384.75a	39.38a	163.75a	335.75a	242.00a
4	252.25a	435.75a	40.38a	167.5a	329.25a	240.75a
P-Value[z]	*0.3692*	*0.1101*	<0.0001	*0.9521*	*0.0031*	0.681
Nutrient solution type						
Sole AE[y]	243.69a	343.56b	36.94b	150.75b	319.63a	
Supplemented AE	262.25a	428.88a	39.31a	177.25a	240.44b	
P-Value	*0.0624*	*0.0021*	*0.0005*	*0.0125*	*<0.0001*	

[z] There was a significant two-way interaction between duration and nutrient solution type on zinc uptake (P=0.0165)

[y] AE=Aquaculture effluent

Table 5.12. Macronutrient uptake efficiency based on plant tissue nutrients in run 1

Duration minutes	N	P	K	Mg	Ca	S
	Efficiency (kg Yield kg^{-1} dry mass)					
1	148.60a[*]	689.82a	85.20a	596.86a	133.27a	1107.74a
2	146.71a	636.13a	86.20a	680.20a	114.30a	982.26a
3	145.64a	616.78a	86.93a	746.27a	117.45a	1022.48a
4	142.95a	556.74a	83.89a	694.12a	120.49a	892.12a
P-Value	*0.8565*	*0.0938*	*0.812*	*0.4894*	*0.1406*	*0.1*
Nutrient solution type						
Sole AE	149.07a	724.77a	86.53ns	944.89a	110.61b	1177.58a
supplemented AE	142.88a	524.96b	84.58	413.84b	132.14a	824.71b
P-Value	*0.1585*	*<0.0001*	*0.4112*	*<0.0001*	*0.0012*	*<0.0001*

[*] Means in the same column followed by the same alphabet are not statistically different (P≥0.05)

5.4.5 Yield and biomass partitioning

Results of the treatments on fruit yield (kg plant^{-1}) and biomass partitioned into fruits, shoot, and leaves (g plant^{-1}) are shown in **Table 5.13**. The results show that although statistically significant (P=0.004), nutrient supplementation led to only 7% higher yield than the sole. A 7% increase in yield due to nutrient supplementation may not be an attractive increase (small effect size) to warrant the additional cost that would be incurred in purchasing fertilizers and an injection system. The yield results obtained in this study corroborate the general observation that aquaculture effluent can produce acceptable yields even without nutrient supplementation (Blanchard et al., 2020; Schmautz et al., 2016). These observed yields by sole AE could also be attributed to the use of biofloc aquaculture effluent which has been demonstrated to promote better plant growth due to the presence of bacterial floc and beneficial algae (Pinho et al., 2021, 2017). Yields were generally higher in experimental run 1 than in run 2 due to an early truncation of trial in run 2 due to spider mites' issues encountered. There were no two-or three-way interaction between duration, nutrient solution type, and experimental run on fruit yield. However, fertigating for 1 minute resulted in a significantly lower fruit yield than the other fertigation durations. Generally, regardless of nutrient solution type, increasing fertigation above 1-minute duration resulted in 27%, 32% and 23% for 2-, 3-, and 4-minute durations, respectively. Therefore, fertigating for 3 minutes duration at half-hourly interval was optimal for the plants for both sole and supplemented AE.

Results of biomass partitioning (**Table 5.13**) show that effect of fertigation duration on fruit, and shoot biomass differed significantly between the two experimental runs. In experimental run 1, fertigating for 1 minute resulted in significantly lower fruit biomass than fertigating for 2 minutes which was not different from fertigating for 3- or 4-minutes. However, in experimental run 2, there were no significant effects of the fertigation durations on fruit biomass. Also, shoot biomass in experimental run 1 was significantly lower for plants fertigated for 1 minute than the other duration levels which remained statistically similar. However, in experiment run 2, shoot biomass was statistically similar between 1- and 2-minutes and between 2-, 3-, and 4-minutes but different between 1-, 3-, and 4-minute duration. Effect of fertigation duration on total aboveground biomass (fruit+leaves+shoot) was similar in trend with leaf biomass. Fertigating for 1-minute duration generally resulted in reduced leaf and total biomass but was not significantly different from 2- or 4-minute duration. Fertigating for 3 minutes resulted in the highest leaf and total biomass but was not significantly different from 2- or 4 minutes.

Generally, the trends observed in biomass partitioning did not assist in explaining yield differences among the fertigation duration levels or the nutrient solution types. Eventually, total biomass remained statistically similar for both sole and supplemented AE supporting the claim that sole AE is capable of engendering good overall performance of the cucumber plants.

Table 5.13. Yield and biomass partitioning of cucumber in response to fertigation duration, fixed effects, and random/covariance estimates

		Biomass (g plant^{-1})					
		Fruit		Leaf	Shoot		Total
	Yield (kg plant^{-1})	Run 1	Run 2		Run 1	Run 2	
Fixed effects							
Fertigation duration (min)							
1	3.81b*	159.41b	135.54a	65.01b	25.14b	16.27b	233.19b
2	4.85a	210.4ab	146.96a	73.22ab	36.4a	19.07ab	279.63ab
3	5.05a	230.97a	146.7a	82.58a	41.98a	20.01a	302.41a
4	4.68a	217.44ab	137.69a	79.59ab	36.41a	20.48a	285.6ab
P-Value	*0.0076*	*0.0372*	*0.6786*	0.027	*0.0061*	*0.0102*	0.0333
Run 1	5.26a	204.56a		66.03b	34.98a		305.57a
Run 2	3.94b	141.72b		84.17a	18.95b		244.85b
P-Value	<.0001	<.0001		<.0001	<.0001		<.0001
Sole AE	4.4b	194.54a	138.38a	72.8a	34.43a	18.29b	265.62a
Supplemented AE	4.79a	214.58a	145.07a	77.4a	35.53a	19.63a	284.80a
P-Value	*0.004*	*0.2091*	*0.3161*		*0.5815*	*0.0238*	*0.085*
P-Values for fixed effects of two-way and three-way interaction							
Duration*Nutrient type	0.2086	0.2066		0.2694	0.7108		0.1812
Duration*Run	0.4591	0.041		0.1798	0.0028		0.0459
Nutrient Type*Run	0.1652	0.4021		0.3613	0.9174		0.7624
Duration*Nutrient type*Run	0.2109	0.2633		0.4874	0.3126		0.2334

*Means in the same column followed by the same alphabet are not statistically different (P≥0.05)

5.5 Conclusion

The study was set out to assess the influence of fertigation duration and nutrient solution type (sole or supplemented aquaculture effluent) on growth, yield and leachate measurements of cucumber. It was identified that plants fertigated with supplemented aquaculture effluent (AE) leached out on average up to 56% and 41% more EC and nitrate N, respectively than those fertigated with sole AE. However, fertigation duration was ineffective at influencing growth parameters, leaf gas exchange measurements. Fertigating for only 1-minute duration resulted in significant yield reduction whereas fertigating for 3 minutes generally promoted higher yields and total aboveground biomass but was not statistically far from yields obtained by fertigating for 1 minute. The effect of fertigation duration on fruit, and shoot biomass depended on experimental runs which were governed by differences in the greenhouse microclimate. Comparing supplemented and sole AE, only a 7% higher yield was obtained due to nutrient supplementation and is considered inadequate to warrant need for nutrient supplementation. Therefore, under the current condition, use of sole AE was adequate to obtain desirable yields of the cucumber plants. Results of tissue macro- and micronutrients as well as leachate nitrate-N and electrical conductivity further suggest that nutrients supplied by sole AE was adequate to support the performance of the plants and nutrient supplementation was not justifiable.

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6.0 General Conclusion

In the first chapter of this dissertation, a synthesis of the literature through a meta-analysis of available results comparing yields of aquaponics and conventional hydroponics was done. The results revealed that, among the factors that affected yield comparison between the two systems were substrate and nutrient supplementation. Studies adopting substrate were generally few with major focus on inorganic substrates since most of the aquaponics systems examined were coupled systems. In the meta-analysis, substrate-based systems offered poor yield advantage of aquaponics over conventional hydroponics. It was identified in another review that time-fertigation information is lacking in the literature probably due to advancement in sensor development, less attention was paid to time-fertigation. Following the needs in the literature, the subsequent chapters offered results for decisions regarding alternative substrates, specifically, pine bark over perlite, and timed-fertigation scheduling in perlite for interval and duration selection when producing greenhouse soilless cucumber.

From the substrate study, it can be concluded that, when optimum plant density of two plants per pot is desired, perlite offers a more suitable option than pine bark. However, in the case where it is economically feasible to adjust plant density through other means than increasing the plants per pot, pine bark would be more suitable. For instance, plant density could be adjusted by training plants to two rather than one stem per plant. Another reason pine bark would be preferred over perlite based on the current results would be to step down pH for downstream use by plants that are sensitive to high pH and where the grower wishes to avoid use of acids for pH regulation. However, in using pine bark as a pH regulator, consideration might be paid on the additional treatment of the effluent that might be required before use. In terms of impact of the substrates on foliar nutritional health, it can be concluded that both pine bark and perlite substrates supported adequate nutrition of the plants as there were no visual or measured nutrient deficiencies. Iron supplementation in the 2016 trial might have alleviated any Fe deficiency resulting in sufficient levels. Foliar boron was lower than lower sufficiency for cucumber in most cases and supplementation with borax or boric acid is recommended. Lower uptake of boron could be due to preferential uptake of other anions such as N, P, and S in the forms of NO_3^--N, $H_2PO_4^-$, and SO_4^- whose uptake also tend to increase the leachate pH due to release of H^+ in the process. Interestingly, in pine bark substrate, which is intrinsically high in sulfur, boron sufficiency reached the lower sufficiency for cucumber in the Spring season suggesting season effect on boron uptake in pine bark.

Fertigation scheduling presented an opportunity to investigate the potential of using time-fertigation to reduce leachate volume without impact on cucumber productivity. Setting the fertigation duration at 4 minutes, intervals of 15, 30, 60, and 90 minutes with hydroponic nutrient solution showed no differential effect on cucumber yield performance. Differential nutrient partitioning to leaves, shoot and fruits was observed for each interval with more sulfur partitioned to leaves at 30 minutes and more boron partitioned to fruits at 60 minutes. However, due to the reduced leachate volume with increasing interval, and increasing cucumber water use efficiency with increasing fertigation interval fertigating every 90 minutes for a 4-minute duration offered the best results.

It was identified that plants fertigated with supplemented aquaculture effluent (AE) leached out on average up to 56% and 41% more EC and nitrate N, respectively than those fertigated with sole AE. However, fertigation duration was ineffective at influencing growth parameters, leaf gas exchange measurements. Fertigating for only 1-minute duration resulted in significant yield reduction whereas fertigating for 3 minutes generally promoted higher yields and total aboveground biomass but was not statistically far from yields obtained by fertigating for 1 minute. The effect of fertigation duration on fruit, and shoot biomass depended on experimental runs which were governed by differences in the greenhouse microclimate. Comparing supplemented and sole AE, only a 7% higher yield was obtained due to nutrient supplementation and is considered inadequate to warrant need for nutrient supplementation. Therefore, under the current condition, use of sole AE was adequate to obtain desirable yields of the cucumber plants. Results of tissue macro- and micronutrients as well as leachate nitrate-N and electrical conductivity further suggest that nutrients supplied by sole AE was adequate to support the performance of the plants and nutrient supplementation was not justifiable.

Appendices

A1. Additional Density trial for leachate measurement

Brief introduction

This trial was an extension of the substrate-density trial described in chapter II but with more focus on leachate volume measurements, yield and foliar analysis. The justification for this trial was that in convention hydroponic production, plant density is usually maintained at two plants per pot to maximize limited greenhouse space. However, given the inherently low nutrient composition of aquaculture effluent, adoption of two plants per pot might not be ideal. The trial also provided an opportunity to assess the relationship between temperature and growth parameters

Materials and Methods

influent measurement

All methodology is as described in Chapter II of this dissertation (Ayipio et al., 2021). Specific measurements related to this study are described below.

Influent was collected using 5-gallon buckets with diameter, width and heigh of 12.5, 12.5, and 14.5 inches respectively

Calculations

Volume=pi.r^2.h

pi=3.142

r=1/2*D=6.25

p.r^2=122.73

this will give us volume in cubic inches but we want it

in gallons. 1 cubic inch = 0.004329 gallons

Water height in the buckets were measured with meter rule (cm) and then converted to volume using the equation above. Since the measurement was in centimeters, it was converted to inches.

1 cm = 0.394 inches

Leachate measurement

Leachate was collected in rectangular troughs placed under a group of 5 plants which were supported with 2” thick plywood. Holes were drilled in the plywood to allow water from the drainage holes of the Dutch buckets flow through to the trough. Water height was measured as in the case of the aquaculture effluent and volume collected determined as Length x width x Height. Water was discarded after each measurement.

Results and discussion

Yield per plant was not different but was higher in one plant than two plants per pot. There were significantly higher leaf and fruit dry mass in one plant than in two plants per pot.

Table A1.1. Effect of number of plants per pot on biomass partitioning and yield

	Dry mass (g plant^{-1})				Yield (kg plant^{-1})	
Density^{z}	Leaf	Shoot	Fruit	Total	Fruit count	Fresh weight
1x	21.4a	13ns	43.53a	77.93a	17.45ns	4.13ns
2x	17.43b	9.6	29.73b	56.77b	14.9	3.55
pooled	0.0102	<0.0001	0.004	0.0011	0.0073	0.0197
sattterthwaite	0.013	<0.0001	0.005	0.002	0.0078	0.0282
Folded F	0.001	0.0497	0.001	0.0003	0.6368	0.0953

^{z}Density refers to number of plants per 11-L Dutch bucket; 1x=one plant per pot; 2x=two plants per pot. Means in the same column followed by the same alphabet are not statistically different (P≥0.05).

Table A2.2. Effect of number of plants per pot on macro-and micronutrient partitioning

	Macronutrient amount (g/plant)						Micronutreints amount (g/plant)				
Density	N	P	K	Mg	Ca	S	Fe	Mn	B	Zn	Cu
						Leaf					
1x	5.03	0.7	3.3	0.6033	6.79	0.46	68.33	123	35	135	11.33
2x	4.75	0.61	2.91	0.6167	7.61	0.407	73	137	37	143	10
pooled	0.07	0.13	0.02	0.63	0	0.004	0.421	0.04	0.3	0.1	0.0161
sattterthwaite	0.08	0.132	0.03	0.6354	0.01	0.004	0.46	0.04	0.3	0.1	0.0572
Folded F	0.6	0.836	0.36	0.5424	0.41	0.857	0.057	0.97	0.4	0.7	.
						Shoot					
1x	2.9	0.617	7.31	0.4733	3.12	0.397	56.33	55.3	23	71	7.67
2x	2.25	0.433	6.75	0.4767	3.21	0.33	65.67	62.7	22	63	7
pooled	0	0.027	0.03	0.874	0.77	0.067	0.401	0.28	0.5	0	0.1161
sattterthwaite	0.01	0.043	0.03	0.8785	0.78	0.074	0.42	0.34	0.5	0	0.1835
Folded F	0.6	0.4	0.78	0.2286	0.18	0.656	0.366	0.05	0.9	0.9	.
						Fruit					
1x	3.25	0.807	4.54	0.267	0.62	0.29	46.67	24	15	45	7
2x	3.14	0.753	4.66	0.253	0.58	0.277	51	23	14	43	6.67
pooled	0.091	0.171	0.05	0.0474	0.29	0.205	0.28	0.29	0.3	0.3	0.3739
sattterthwaite	0.101	0.206	0.08	0.0474	0.33	0.207	0.235	0.29	0.4	0.3	0.4226
Folded F	0.619	0.32	0.32	1	0.08	0.856	0.094	1	0.3	0.5	.
						total					
1x	11.2	2.123	15.5	1.3433	10.5	1.147	171.3	203	73	251	26
2x	10.1	1.797	14.3	1.3467	11.4	1.013	189.7	223	73	249	23.67
pooled	0.01	0.053	0.02	0.9148	0.02	0.037	0.187	0.11	1	0.8	0.0249
sattterthwaite	0.01	0.061	0.02	0.9151	0.03	0.038	0.25	0.15	1	0.8	0.0357
Folded F	0.42	0.636	0.88	0.7273	0.54	0.859	0.032	0.28	1	0.8	0.5

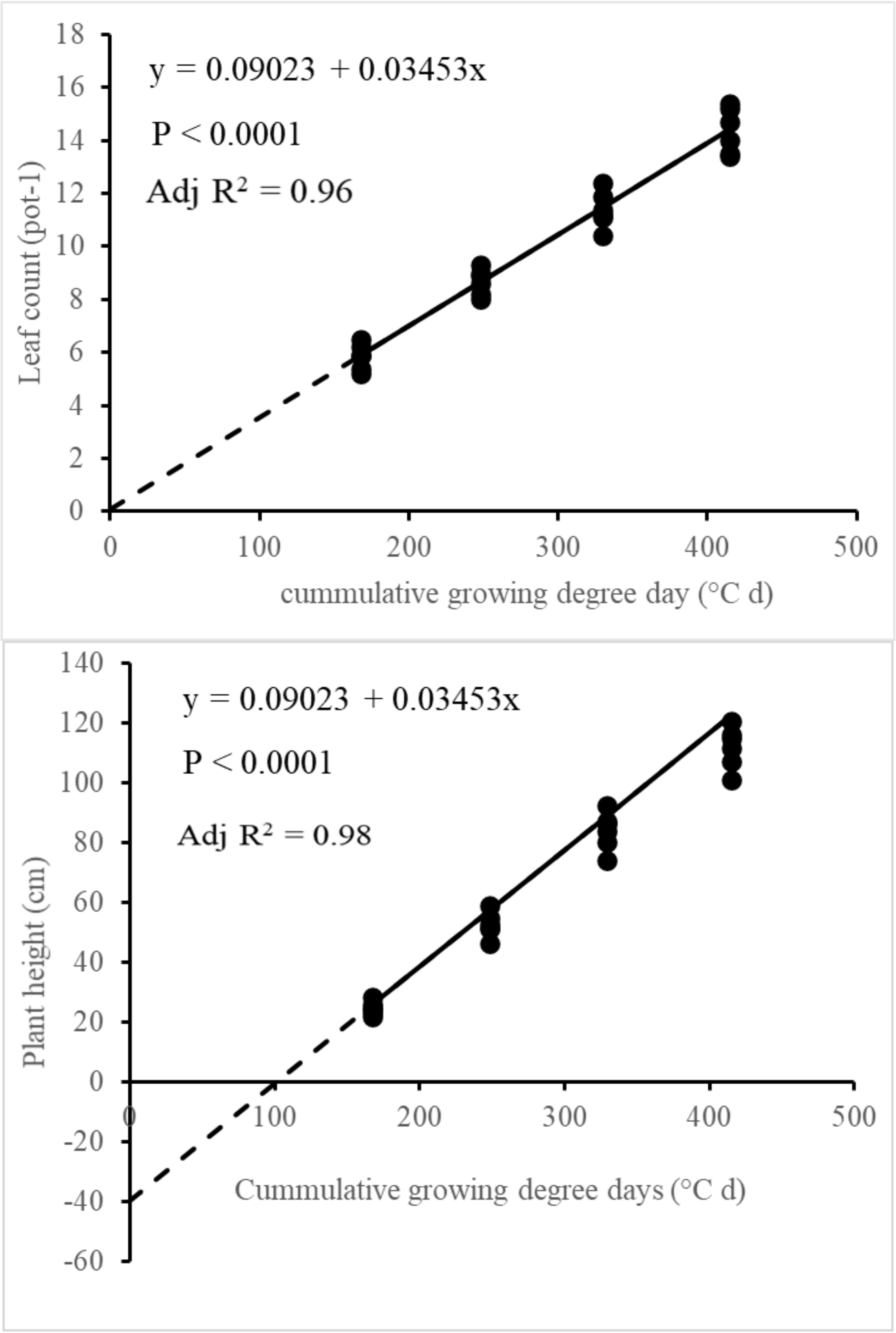


Figure A1. Relationship between temperature sum, and 1) leaf count (upper panel) and 2) plant height (lower panel)

A2. Modeling fertigation needs of cucumber in aquaponics

Water refill needed in aquaponics is controlled by water evaporated from the fish tank and clarifier surface, losses from sludge discharge and leakages, water transpired and/or water taken out when cucumber fruits are harvested, and drainage out of plants. The focus is on the plant production aspect only where cucumber plants are grown in Dutch buckets filled with 100% perlite. The approach to the system for optimized water and nutrient use is described below.

Modeling Approach

System Components

Scheme

i) Substrate volume defined by volume of Dutch bucket (m^3 m^{-2}, L m^{-2})

ii) Drainage system collecting substrate effluent for measurement (L m^{-2})

iii) Sump Pump (P_S) delivering water is controlled by timer clock (preset interval and duration)

iv) irrigation system defined by emitters geometry and discharge rate (Q_{in})

State Variables

- Nutrient concentrations (mg L^{-1})
- Actual water volume of fertigation source (L m^{-2})
- Actual water volume in substrate (L m^{-2})
- Drainage volume (L m^{-2})

Dynamic Variables

- Threshold EC (EC_{thr}, dS m^{-1})
- Threshold nutrient concentration (mg L^{-1})
- Substrate parameters; hydraulic conductivity (K_h, cm h^{-1}), water retention function

- Ion parameters (N); effective ion diffusion coefficient
- Crop parameters; crop uptake, dry matter, and N partitioning coefficients

Processes

- **Evapotranspiration (ET, L m^{-2} ground h^{-1} or d^{-1})**
- Water uptake rate (Kg m^{-2} ground h^{-1} or d^{-1})
- Ion uptake rate (Kg m^{-2} ground h^{-1} or d^{-1})
- Ion portioning between substrate solution and solid phase
- **Water transport in substrate**
- Ion transport in substrate
- **Crop growth rate and dry matter production (Kg m^{-2} ground h^{-1} or d^{-1})**
- Root extension in substrate (Kg m^{-2} substrate h^{-1} or d^{-1})

Dry matter production and partitioning

The concept was built on the generally accepted and simplified light use efficiency approach for dry matter production (Marcelis et al., 1998; Kage et al., 2000) under non-limiting nutrients and water supply.

Rate of dry matter production is calculated as a linear function of absorbed photosynthetically active radiation (PAR) Q (MJ m^{-2} d^{-1}) and light use efficiency **ε** (g MJ^{-1}) given as

$$\frac{dW}{dt} = Q \bullet \varepsilon \qquad \textbf{(1)}$$

The amount of absorbed PAR (Q) is calculated from the incoming radiation above the plant canopy S (MJ m^{-2} d^{-1}) and the leaf area index LAI (m^2 m^{-2}) as

$$Q=S\bullet(1-e^{-k\bullet LAI}) \qquad (2)$$

Incoming radiation is either measured or estimated from outside global radiation (GR) considering the greenhouse transmissivity, t, and fraction of PAR in the total radiation spectrum, f_{PAR} as

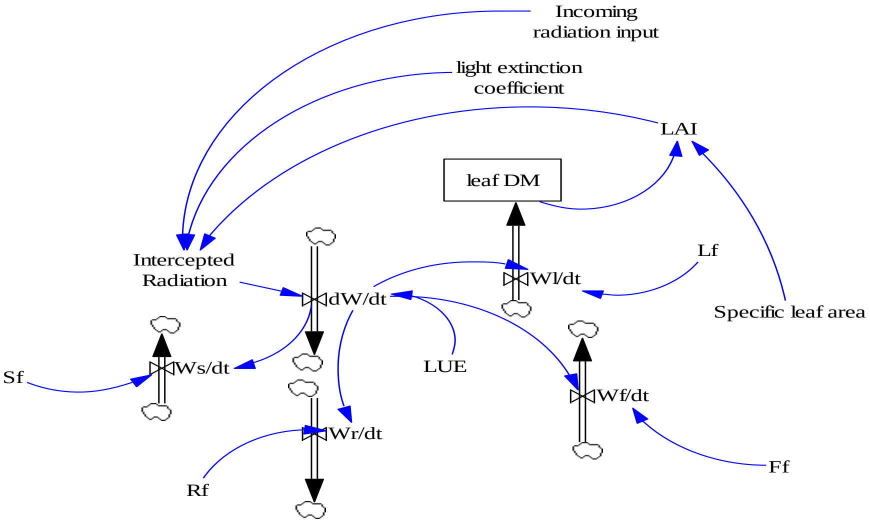
$$S = GR \bullet t \bullet f_{PAR} \qquad (3)$$

Dry Matter Partitioning

The total growth rate of a plant dW_t/dt is the sum of the growth rates of all organs partitioned as weight of stem W_S/dt, leaf W_L/dt, and root W_R/dt representing the vegetative growth and fruits dF/dt representing the generative growth. In simplified form, dry matter growth rate of any organ, i, dW_i/dt is obtained by expressed as a fraction f_i of the total dry matter growth rate dW_t/dt as

$$\frac{dW_i}{dt} = \frac{dW_t}{dt} \bullet fi \qquad (4)$$

relational diagrams for the above-described equations are implemented in vensim as illustrated in Figure **A2.1**.



Dry Matter Production and Partitioning

Figure A2.1. Relational diagram of dry matter production and partitioning for a well watered and fertilized plant

Fraction of dry matter allocated specific organs depends on growth stage of the plant which is a function of the temperature sum the plant has experienced.

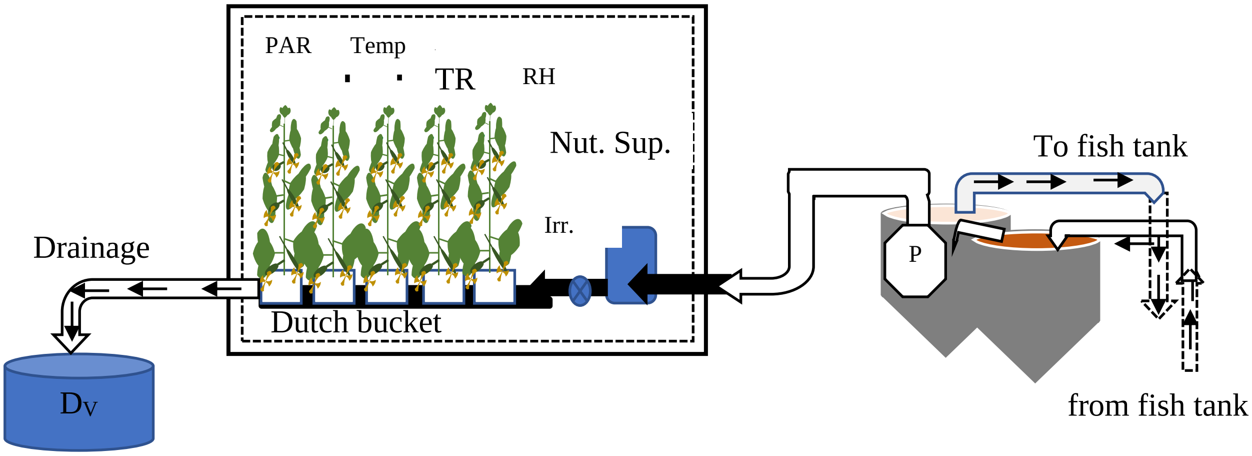


Figure A2.2. Schematic of system at Auburn University aquaponics facility. P=pump; nutrient supplementation system (Nut. Sup.) used to add nutrients when necessary. Directional arrows show flow of water or dissolved nutrients. D_v is drainage volume, which is discarded, used for algae production or field application. Input necessary for dry matter production is photosynthetically active radiation (PAR); temperature (temp) is incorporated for growth stage calculation dependence on temperature sum. Relative humidity (RH) with temperature for vapor pressure deficit calculation involved in estimating crop transpiration.

Crop evapotranspiration (ETc)

Given the above setup, crop evapotranspiration can be estimated as the difference between total irrigation volume and drainage (eq. 5). However, this is prone to measurement errors due to variability in emitter discharge rate, and clogging during production.

$$ETc = Irr - D_v \tag{5}$$

ETc is sometimes based on the Penman-Monteith (PM) equation using the greenhouse climate data; PAR, temperature and relative humidity as inputs and canopy parameters such as leaf area index (LAI) of the plant either as a measured data or calculated from dry matter partitioning described above, aerodynamic and canopy resistances (r_a and r_c respectively). Kage et al. (2000) divided the PM equation into two components following McNaughton (1986), namely equilibrium transpiration ($E_{eq,}$ kg m^{-2} s^{-1}) and imposed transpiration (E_{imp} kg m^{-2} s^{-1}). Equilibrium transpiration is based solely on net radiation as an input whereas imposed transpiration is based on vapor pressure gradient e_s-e_a above the plant canopy. Total transpiration is the sum of imposed and equilibrium transpiration. Relational diagram of crop evapotranspiration using the Penman-Monteith equation is present in **Figure A2.3**.

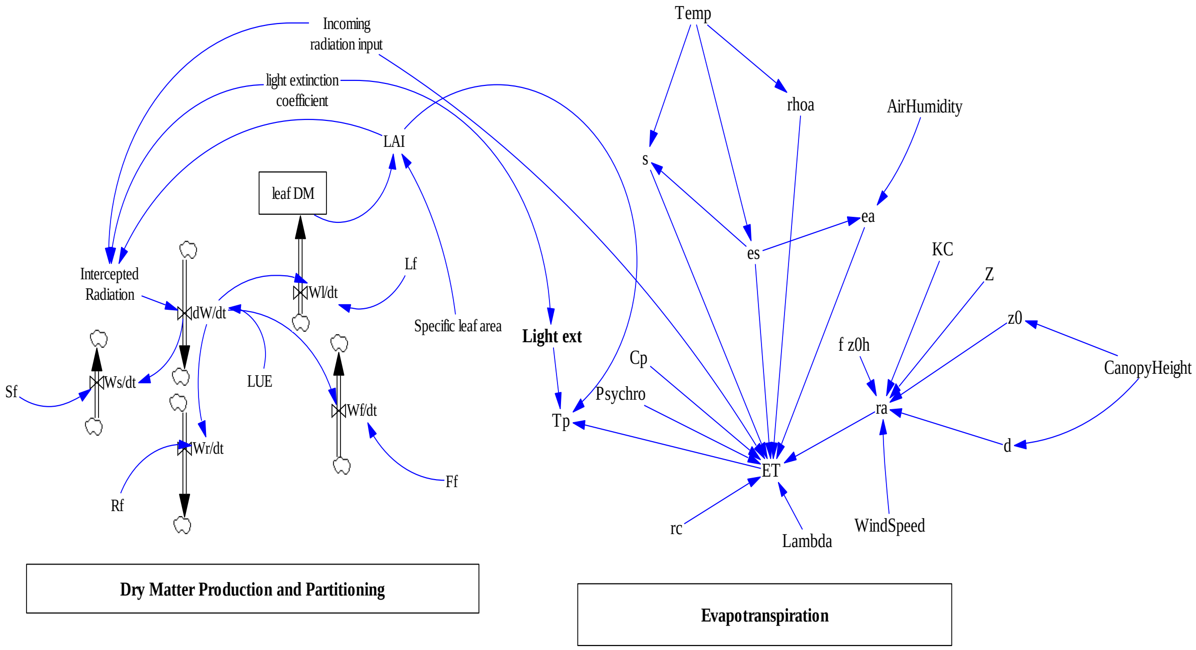


Figure A2.3. Relational diagram of crop evapotranspiration (right) based on Penman-Monteith equation coupled with biomass production and partitioning (left) to show link between the two.

Water and nutrient mass balance in the substrate

Once transpiration (or crop evapotranspiration) is estimated, it used in the water balance model for the growing media (substrate). For optimal system control, nutrient ion concentration in aquaculture effluent (C_{ae}) and supplementation (C_s) alongside their volumes (V_{ae} and V_s, respectively) must be known.

The balance for water volume in the substrate system is then given as

$dV_{ae}/dt=Irr_{in}-Q_{dv}-ET$ (6)

where V_{ae}=volume of aquaculture effluent in substrate;

Irrin = is the volume of incoming aquaculture effluent defined by discharge rate (R) and fertigation amount which depends on number of events per day or duration of fertigation event. Qdv is the drainage rate or drainage amount. ET is crop evapotranspiration.

The ion balance is given in like manner as

$dC_{ni}/dt = [C_{ni}\bullet Irr_{in-} C_{ni}\bullet Q_{dv}-Upt_{ni}]/V_{ae}$ (7)

Here, Uptni=uptake rate of the ion (g m-2 d-1); all other parameters as described earlier.