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Evaluation of different artificial light technologies for indoor aquaponic production of Bibb lettuce, *Lactuca sativa* var. *capitata*, and compact basil, *Ocimum basilicum* var. *Genovese*

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Abstract

Aquaponic production in temperate climates is often conducted in insulated buildings to reduce heating costs and therefore must rely on artificial lighting to replace natural sunlight. However, there are several different light technologies available to producers. We conducted two aquaponic growth trials to compare four lighting technologies for the indoor production of Bibb lettuce, *Lactuca sativa* var. *capitata* (Trial 1), and basil, *Ocimum basilicum* var. *Genovese* (Trial 2). Light types evaluated included metal halide (MH), fluorescent (FLO), light-emitting diode (LED), and induction (IND). Using a complete block design, each of the four identical aquaponic systems included all four light types. Juvenile Nile tilapia, *Oreochromis niloticus*, (Trial 1:145 g; Trial 2:169 g) were stocked into each replicate system and fed at a rate of 60 g feed m^{-2} of plant grow-space per day. In Trial 1, Bibb lettuce plants grown under LED lights had significantly higher ($p \le 0.05$) average individual weights (164 g), higher production per unit area (3118 g m^{-2}), and higher production per unit energy (84 g m^{-2} kWh^{-1}) compared to those grown under the other light types. Bibb lettuce grown under IND and FLO lights had significantly higher ($p \le 0.05$) average individual weights (82.0 and 78.0 g, respectively) and production per unit of area (1762 and 1700 g m^{-2}, respectively) than those grown under MH lights (1382 g m^{-2}). In Trial 2, Basil grown under LED lights had significantly higher ($p \leq 0.05$) average individual weights (188 g), production per unit area (4970 m^{-2}), and production per unit of energy (1483 g m^{-2} kWh^{-1}) than basil grown under the other three light types. There was no significant difference ($p > 0.05$) in average individual weight or production per unit area among basil plants grown under MH, IND or FLO. Analysis of leaf tissues indicated several statistically significant differences among the light treatments. However, the actual magnitudes of these differences were relatively small. Evaluation of emitted wavelengths indicate that production differences may be related to the amount of red light spectra (600–699 nm), and the ratio of red light to blue light (400–499 nm) (R:B ratio) produced by the different light types. The LED had a greater production of red spectra and higher R:B ratios than other lights which appears to be advantageous for growth of Bibb lettuce and basil.

KEYWORDS
aquaponics, artificial lights, indoor production

1 | INTRODUCTION

Aquaponics integrates the culture of food-fish in tanks with soilless plant production in a recirculating system (Rakocy et al., 2006). The majority of research in aquaponics has been performed on systems located outdoors in tropical climates or in greenhouses and high tunnels in sub-tropical climates. These systems all receive some level of natural light. However, year-round production in temperate climate often requires the use of insulated buildings to reduce heating costs. In these situations, artificial light must be provided to fully replace sunlight. While the need for artificial lights adds additional overhead and investment costs, the ability to build aquaponic farms near or within large urban centers could potentially reduce supply chain costs and improve access to fresh protein and produce for urban populations (Canning et al., 2010).

Several different types of grow lights have been used for indoor plant production, including metal halide (MH), fluorescent (FLO), induction (IND), and light-emitting diode (LED; Ruangrak & Khummueng, 2019). Metal halide fixtures provide light in a spectral range suitable for many plant species (350–750 nm). Fluorescent lights typically operate at white or daylight color temperatures (≥5000 Kelvin), can provide significant photosynthetically active radiation (PAR), and are relatively inexpensive (Fukuda, 2013). However, they have been found to be insufficient for growth of many flowering plants (Vandre, 2011). Induction lights are typically comparable in output to FLO lights, but the electrode-less design can provide up to 100,000 h of functional life from a single bulb (compared to ≤15,000 h for FLO). Senders et al., (2011) found that IND lights produced more compact plants with thick leaves, compared to plants grown under MH and FLO lights. Light-emitting diodes have become more popular based their extended lifespan, low heat output, and relatively low energy use compared to other types of grow lights. LEDs can produce more compact plants than FLO lights and the spectral output can be customized to specific plant requirements (Fang & Jao, 2000). While these light types have been evaluated independently or compared in other contexts (e.g., supplemental lighting for greenhouse production), they have not been directly compared in terms of effectiveness and efficiencies in aquaponic systems for the plant crops most widely produced in those systems.

The objective of this study was to directly compare in aquaponic plant production four of the most widely used artificial light technologies. Light types (FLO, MH, IND, and LED) were compared in terms of plant growth, total biomass, root: shoot ratios, energy use, plant production per unit of energy, and chemical composition of harvested plant biomass. We evaluated Bibb lettuce (*Lactuca sativa* var. *capitata*) in Trial 1 and basil (*Ocimum basilicum* var. *Genovese*) in Trial 2.

2 | MATERIALS AND METHODS

Two independent trials were conducted to compare four light sources on two different plant crops (Trial 1, Bibb lettuce and Trial 2, basil). Shared protocols are listed here. The details specific to Trials 1 and 2 are then addressed separately below.

2.1 | System components

Each study utilized four identical aquaponic systems (Figure 1) consisting of one 415 L fish tank, one 190 L clarifier, one 115 L mineralization tank, a 180 L sump (Polytank; Litchfield, MN) and two 454 L hydroponic troughs (Red Ewald; Karnes City, TX). There were two floating rafts (5 cm polystyrene foam board) per hydroponic trough for a total of four rafts per aquaponic system (2.7 m^2 of total raft space per system). Each system was driven by one Model 4000 Quite One Lifegard Pump (Lifegard Aquatics; Santa Fe Springs, CA) located in the sump. The pump lifted water into the fish tank, with gravity flow through all other components back to the sump.

2.2 | Light technologies

All four light technologies were included within all four aquaponic systems in a complete block design (Steele & Torrie, 1980). Each raft/light combination was enclosed on three sides to prevent light contamination between treatments. Specific lights evaluated were: (1) MH: 400 watt, 7200 K Plantmax bulb (New Earth; Louisville, KY), (2) IND: 3020 K bulb (Brotherhood Products; Los Angeles, CA); (3) FLO: 54-watt, 6500 K T5 bulb (New Earth; Louisville, KY); and (4) LED: 54 Surexi F3 bulbs (Illumitex; Austin, TX). The height of the lights was adjusted so that all provided a photosynthetic photon flux density (PPFD) of 200 μmol m^{-2} sec^{-1} (200 mmol/m2/sec) at the top leaves, as measured using a LP-80 PAR/LAI Ceptometer (Decagon Devices, Inc.; Pullman, WA). As plants grew, light heights were adjusted two times per week based on PPFD readings. Energy use for each light was recorded using a P3 Kill-A-Watt model p4400 power usage monitor (P3 International; New York, NY).

2.3 | Fish and plant materials

Approximately two weeks before the planned stocking date for each trial, plant seeds were sown into rockwool cubes (ROCKWOOL International; Hedehusene, Denmark) and raised under FLO lights until the first true leaves emerged. Plants were randomly assigned to treatments and stocked into floating raft beds at 18 seedlings per raft (72 plants per system or 26.4 plants m^{-2}).

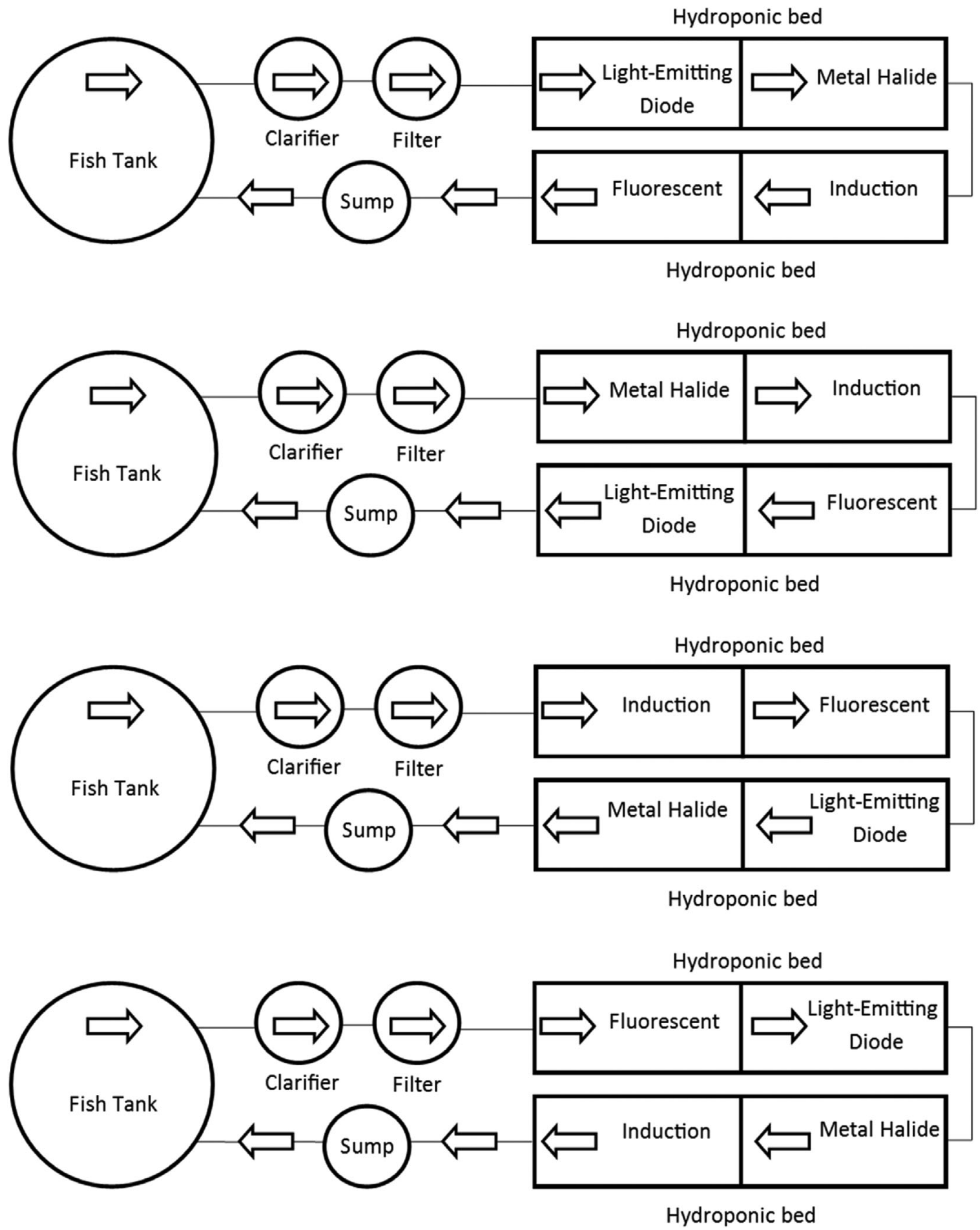

FIGURE 1 Configuration of the four aquaponic systems and lights, arranged in randomized complete block design. LED, light-emitting diode; MH, metal halide; IND, induction; and FLO, fluorescent. Significant differences ($p \leq 0.05$) are indicated by different letters within rows

One day prior to stocking of both fish and plants, water from all four systems was pumped into a large tank, homogenized, and then redistributed. On Day 0 all-male fingerling Nile tilapia, (*Oreochromis niloticus*) were stocked into fish tanks at a density calculated to support a feed rate of 60 g of floating fish feed per m^2 of vegetable grow space per day (Rakocy et al., 2003). Fish were fed a floating 32% protein commercial fish feed (Rangen Inc.; Buhl, ID) twice daily. Fish used in this study were spawned at the Aquaculture Research Center at Kentucky State University using YY male *O. niloticus*.

2.4 | Measurements and calculations

Water quality was measured daily for each system using water from the sump. Tested variables included dissolved oxygen (DO) and temperature (Pro 2030 m YSI; Yellow Springs, OH), electrical conductivity (EC) (Bluelab Corporation Limited; Tauranga, New Zealand), and pH (Accumet AP71; Fisher Scientific, Hampton, NH). Total ammonia-N (TAN), nitrite-N (NO_2-N), nitrate-N (NO_3-N), and iron were measured three times per week using a HACH DR/2000 spectrophotometer (HACH Company; Loveland, CO). Alkalinity was measured three times per week using a HACH digital titrator (HACH Company; Loveland, CO). To maintain pH near 7.0, systems were supplemented with potassium hydroxide (KOH) and calcium hydroxide ($Ca[OH]_2$). If iron concentrations dropped below 1.0 mg L^{-1}, chelated iron was added. Air temperature and humidity above each raft were also monitored daily using a hygrometer (Sper Scientific; Scottsdale, AZ).

At the end of each trial, all plants were removed, stalks were cut above and below the rockwool cubes. Shoots (leaves, stems) and roots were weighed separately to the nearest 0.1 g using a New Classic MS12001L scale (Mettler Toledo; Columbus, OH).

The four center plants under each light also had dry biomass determined using a DEC5-32 drying oven (Hobart; Troy, OH) at a constant temperature of 70°C for 72 h (Arshadullah et al., 2011). Root to shoot ratios were calculated by dividing the dry root weight by the dry leaf weight as harvested. Dried plant tissues were analyzed for nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, manganese, boron, copper, zinc, and molybdenum by a commercial laboratory (Micro Macro International; Athens, GA).

At the end of each trial, all fish in each system were removed, counted, and weighed. Fish performance was based on daily percentage weight gain (g), survival (%), and specific growth rate (SGR, % day^{-1}). Specific growth rate was calculated as SGR% = (ln(harvest weight) − ln(stock weight)/# days in study)*100.

2.5 | Stocking: Trial 1

The fish tanks were stocked at 91.6 fish m^{-3}. The juvenile tilapia had an average initial body weight of 145 g resulting in a total tank biomass of 6069 g. Plants were Bibb lettuce, *Lactuca sativa* var. *capitate*, (Johnny's Select Seeds; Winslow, ME).

2.6 | Environmental conditions: Trial 1

Over the 14-day trial, water quality variables averaged (±SD): temperature 25.8 ± 0.2°C; DO 6.0 ± 0.5 mg L^{-1}; pH 7.1 ± 0.2; total ammonia-N 0.2 ± 0.1 mg L^{-1}; nitrite-N, 1.0 ± 0.9 mg L^{-1}; nitrate-N 31.2 ± 9.4 mg L^{-1}; EC 0.89 ± 0.04 mS cm^{-1}, alkalinity 31.5 ± 5.5 mg L^{-1}; and iron 2.1 ± 0.3 mg L^{-1}. These values represent conditions suitable for the culture of Nile tilapia and leafy green plants (Rakocy et al., 2003).

2.7 | Stocking: Trial 2

The fish tanks were stocked at 78.3 fish m^{-3} using juvenile tilapia with an average individual body weight of 169 g resulting in a total tank biomass of 6070 g. The plant evaluated was Genovese compact basil, *Ocimum basilicum* var. *Genovese*, (Johnny's Select Seeds; Winslow, ME).

2.8 | Environmental conditions: Trial 2

Over the 28-day trial, water quality variables averaged (±SD): temperature 26.4 ± 1.3°C; DO 5.4 ± 0.7 mg L^{-1}; pH 7.0 ± 0.2; total ammonia-N 0.2 ± 0.2 mg L^{-1}; nitrite-N, 0.4 ± 0.2 mg L^{-1}; nitrate-N 36.8 ± 5.3 mg L^{-1}; EC 1.0 ± 1.0 mS cm^{-1}, alkalinity 24.7 ± 6.0 mg L^{-1}; and iron 4.1 ± 1.2 mg L^{-1}. These values represent conditions suitable for the culture of Nile tilapia and leafy green plants (Rakocy et al., 2003).

2.9 | Analysis

The effects of light type on plant growth in each of the trials was analyzed as a complete block design and compared using analysis of variance (ANOVA; Steele & Torrie, 1980). If ANOVA indicated significant differences, Fisher's Least Significant Difference test was used to separate means (Steele & Torrie, 1980).

3 | RESULTS

3.1 | Trial 1: Bibb lettuce

Over the 14-day trial, tilapia had 100% survival. The average daily gain was 2.7 ± 0.2 g day^{-1}, specific growth rate (SGR) was 1.5 ± 0.1% day^{-1}, and feed conversion ratio (FCR) was 1.6 ± 0.1. Average total fish biomass at harvest was 7495 g with an average individual weight of 196.0 g. Over the study period, the fish consumed an average of 1.5% of harvested body weight.

Bibb lettuce grown under LED lights achieved significantly higher ($p \le 0.05$) average individual weights (163.6 g) and higher production per unit of area (3118 g m^{-2}) than lettuce grown under the other three light types (Table 1). Lettuce plants grown under IND and FLO lights had significantly higher ($p \le 0.05$) average individual weights (82.0 and 78.0 g, respectively) and higher production per unit of area (1762 and 1700 g m^{-2}, respectively) than plants grown under MH lights. Root-shoot ratios for Bibb lettuce grown under LED lights (0.2) were significantly greater ($p \le 0.05$) than for plants grown under the other three light types, which did not differ significantly ($p > 0.05$).

Energy use (kWh day^{-1}) was significantly higher ($p \le 0.05$) for FLO than among other light types. Energy use by MH was significantly greater than by IND or LED, which were not significantly different ($p > 0.05$). Plants grown under LED had significantly higher ($p \le 0.05$) plant production per unit energy (84 g m^{-2} kWh^{-1}) than any other treatment. Plants grown under IND lights had a significantly higher ($p \le 0.05$) production per unit energy (46 g m^{-2} kWh^{-1}) than those grown under MH (32 g m^{-2} kWh^{-1}) or FLO (33 g m^{-2} kWh^{-1}), which did not differ significantly ($p > 0.05$).

Results for the effects of light type on analyzed composition of leaf tissues in Bibb lettuce are presented in Table 2. Concentrations of P, K, Mg, S, Fe, Mn, and Zn were within expected ranges for Bibb lettuce under all light treatments (Bryson et al., 2014; Table 2). Concentrations of Ca and Cu were lower, and Mo was higher, than expected levels in plant tissue among all light treatments (Table 2). Total N was higher than expected ranges in MH while FLO, LED, and IND were within expected range (Table 2). Plant leaf tissue of K were within the expected range in the LED treatment but below the expected range in the MH, IND, and FLO treatments (Table 2).

3.2 | Trial 2: Basil

Tilapia had 100% survival for the 28-day study period. The average daily gain was 3.0 ± 0.3 g day^{-1}, SGR was 1.9 ± 0.1% day^{-1}, and FCR was 1.5 ± 0.1. Average total fish biomass at harvest was 9136 g with an average individual weight of 283.3 g. Over the study period, the fish consumed an average of 2.0% of harvested body weight.

TABLE 1 Trial 1: Mean (±SE) average individual plant weight (g), plant weight (g) per square meter, root:shoot ratio, average kilowatt hours used per day, and plant biomass (g) per square meter per kilowatt hour for Bibb lettuce (*Lactuca sativa*) grown under four different types of grow lights

Plant variable	LED	MH	IND	FLO
Avg ind weight (g)	163.6 ± 9.0^{a}	59.8 ± 5.2^{c}	82.0 ± 6.2^{b}	78.0 ± 4.6^{b}
Wt per unit area (g m^{-2})	3118 ± 104^{a}	1382 ± 115^{c}	1762 ± 142^{b}	1700 ± 206^{b}
Root:shoot	0.20 ± 0.04^{a}	0.08 ± 0.01^{b}	0.08 ± 0.01^{b}	0.09 ± 0.03^{b}
Avg kWh day^{-1}	3.4 ± 0.0^{c}	3.9 ± 0.0^{b}	3.4 ± 0.1^{c}	4.6 ± 0.2^{a}
Plant wt g m^{-2} kWh^{-1}	83.5 ± 2.6^{a}	32.1 ± 2.8^{c}	46.2 ± 3.8^{b}	33.3 ± 4.9^{c}

TABLE 2 Trial 1: Mean (± SD) of nutrients in Bibb lettuce (*Lactuca sativa*) plant leaf tissues grown under four different types of plant grow lights

Variable	Expected range[a]	LED	MH	IND	FLO
Total N %	3.50–5.50	5.1 ± 0.2^{c}	6.1 ± 0.1^{a}	5.6 ± 0.1^{b}	5.0 ± 0.4^{c}
P %	0.25–0.50	0.9 ± 0.1^{a}	0.8 ± 0.1^{b}	0.8 ± 0.1^{b}	0.8 ± 0.1^{ab}
K %	3.00–4.50	4.2 ± 0.2^{b}	4.8 ± 0.1^{a}	4.8 ± 0.9^{a}	4.7 ± 0.8^{a}
Ca %	2.50–3.50	1.7 ± 0.1^{a}	1.3 ± 01^{bc}	1.2 ± 0.1^{c}	1.4 ± 0.1^{b}
Mg %	0.30–1.00	0.4 ± 0.0^{a}	0.4 ± 0.0^{bc}	0.3 ± 0.0^{c}	0.4 ± 0.0^{b}
S %	0.19–0.29	0.1 ± 0.1^{ab}	0.1 ± 0.0^{ab}	0.1 ± 0.0^{b}	0.2 ± 0.1^{a}
Fe mg L^{-1}	50–200	75.0 ± 2.9^{a}	83.2 ± 15.6^{a}	73.0 ± 6.2^{a}	83.2 ± 2.0^{a}
Mn mg L^{-1}	50–250	134.6 ± 17.8^{a}	93.6 ± 11.7^{b}	88.6 ± 6.4^{b}	100.8 ± 106^{b}
B mg L^{-1}	30–85	35.2 ± 2.5^{a}	27.4 ± 3.2^{b}	26.2 ± 1.5^{b}	28.4 ± 1.6^{b}
Cu mg L^{-1}	5–15	4.6 ± 0.8^{a}	3.9 ± 0.6^{ab}	3.3 ± 0.2^{b}	3.6 ± 0.6^{b}
Zn mg L^{-1}	5–200	26.2 ± 6.4^{a}	32.8 ± 12.5^{a}	24.8 ± 4.1^{a}	28.9 ± 4.3^{a}
Mo mg L^{-1}	0.15–0.42	1.8 ± 0.0^{a}	1.4 ± 0.4^{ab}	1.1 ± 0.2^{b}	1.3 ± 0.2^{b}

Note: Means within a row followed by different superscript letters are significantly different (p < 0.05).
Abbreviations: LED, Light emitting diode; MH, metal halide; IND, induction; FLO, fluorescent (FLO). Abbreviations for minerals and nutrients: B, Boron; Ca, Calcium; Cu, Copper; Fe, Iron; K, Potassium; Mg, Magnesium; Mn, Manganese, Mo, Molybendum; N, Nitrogen; P, Phosphorous; S, Sulfur; Zn, Zinc.
[a]Bryson et al., (2014).

Basil grown under LED lights achieved significantly higher ($p \le 0.05$) average individual weights (188.2 g) and production per unit of area (4971 g m^{-2}) than basil grown under the other three light types (Table 3). There was no significant difference ($p > 0.05$) in average individual weight or production per unit area among plants grown under MH, IND, or FLO. Root-shoot ratios did not differ significantly for plants grown under any of the four light treatments ($p > 0.05$).

Energy use (kWh day^{-1}) was significantly higher ($p \le 0.05$) for FLO than among other light types. Energy use by MH was significantly greater than by IND or LED, which were not significantly different ($p > 0.05$). Production of basil per unit of energy was significantly higher ($p \le 0.05$) for LED (1483 g m^{-2} kWh^{-1}) than for all other treatments. Production per unit of energy was significantly higher ($p \le 0.05$) for IND (588 g m^{-2} kWh^{-1}) than it was for MH (465 g m^{-2} kWh^{-1}) or FLO (444 g m^{-2} kWh^{-1}) which did not differ significantly from each other ($p > 0.05$).

Results for the effects of light type on analyzed composition of leaf tissues in Bibb lettuce are presented in Table 4. The analysis of basil leaf tissue indicated that values for K, Mg, S, Fe, B, An, and Mn were within expected ranges for macro and micro-nutrients in plant leaf tissue in all treatments (Bryson et al., 2014; Table 4).

TABLE 3 Trial 2: Mean (± SE) average individual plant weight (g), total plant weight (g) per square meter, root: shoot ratio, average kilowatt hours used per day, and plant biomass (g) per square meter per kilowatt hour for basil (*Ocimum basilicum* var. *Genovese*) grown under four different types of grow lights

Plant variable	LED	MH	IND	FLO
Avg ind wt (g)	188.2 ± 23.5^{a}	63.0 ± 12.9^{b}	73.3 ± 11.6^{b}	77.0 ± 12.0^{b}
Wt/unit area (g m^{-2})	4971 ± 641^{a}	1790 ± 355^{b}	2004 ± 316^{b}	2056 ± 290^{b}
Root:shoot	0.04 ± 0.01^{a}	0.04 ± 0.01^{a}	0.04 ± 0.02^{a}	0.04 ± 0.01^{a}
Avg kWh day	3.4 ± 0.0^{c}	3.9 ± 0.0 ^{b}	3.4 ± 0.1^{c}	4.6 ± 0.2^{a}
Plant wt g m^{-2} kWh^{-1}	1483.4 ± 187.1^{a}	464.6 ± 96.4^{c}	587.9 ± 86.2^{b}	444.4 ± 52.0^{c}

Note: Significant differences ($p \leq 0.05$) are indicated by different letters within rows.
Abbreviations: IND, induction; FLO, fluorescent; LED, Light-emitting diode; MH, metal halide.

TABLE 4 Trial 2: Mean (±SD) of nutrients in basil (*Ocimum basilicum* var. *Genovese*) plant leaf tissues grown under four different types of plant grow lights

Variable	Expected range[a]	LED	MH	IND	FLO
Total N %	3.50–5.50	4.8 ± 0.4^{a}	4.5 ± 0.3^{a}	4.5 ± 0.4^{a}	4.9 ± 0.2^{a}
P %	0.25–0.50	1.8 ± 0.1^{a}	1.5 ± 0.1^{b}	1.7 ± 0.2^{ab}	1.6 ± 0.1^{ab}
K %	3.00–4.50	3.8 ± 0.1^{b}	4.3 ± 0.2^{a}	4.5 ± 0.2^{a}	4.3 ± 0.2^{a}
Ca %	2.50–3.50	2.1 ± 0.1^{a}	1.7 ± 0.1^{b}	1.8 ± 0.2^{b}	1.0 ± 0.2^{b}
Mg %	0.30–1.00	0.4 ± 0.0^{a}	0.4 ± 0.1^{bc}	0.3 ± 0.0^{c}	0.4 ± 0.0^{b}
S %	0.19–0.29	0.3 ± 0.0^{a}	0.1 ± 0.1^{b}	0.2 ± 0.0a^{b}	0.2 ± 0.2^{ab}
Fe mg L^{-1}	50–200	76.0 ± 5.2^{a}	82.2 ± 1.6^{a}	78.3 ± 2.1^{a}	82.1 ± 5.9^{a}
Mn mg L^{-1}	50–250	55.2 ± 8.0^{a}	40.6 ± 8.2^{a}	46.4 ± 10.5^{a}	44.6 ± 13.8^{a}
B mg L^{-1}	30–85	29.9 ± 0.6^{c}	32.7 ± 6.5^{b}	36.3 ± 1.8^{a}	33.3 ± 1.1^{b}
Cu mg L^{-1}	5–15	3.7 ± 1.6^{a}	4.3 ± 2.2^{a}	3.6 ± 3.1^{a}	3.8 ± 3.1^{a}
Zn mg L^{-1}	5–200	36.4 ± 5.9^{a}	32.4 ± 6.5^{a}	30.5 ± 9.8^{a}	32.9 ± 6.9^{a}
Mo mg L^{-1}	0.15–0.42	0.2 ± 0.0^{a}	0.2 ± 0.1^{a}	0.2 ± 0.0^{a}	0.1 ± 0.0^{a}

Note: Means within a row followed by different superscript letters are significantly different ($p < 0.05$).
Abbreviations: IND, induction; FLO, fluorescent; LED, Light-emitting diode; MH, metal halide. Abbreviations for minerals and nutrients: B, Boron; Ca, Calcium; Cu, Copper; Fe, Iron; K, Potassium; Mg, Magnesium; Mn, Manganese, Mo, Molybendum; N, Nitrogen; P, Phosphorous; S, Sulfur; Zn, Zinc.
[a]Bryson et al. (2014).

The levels of P were higher than the expected ranges while Ca and Cu were lower (Table 4). Potassium (K) was significantly lower ($p \leq 0.05$) in basil from the LED treatment compared to those in the other three treatments, which did not differ significantly ($p > 0.05$). Calcium (Ca) was significantly higher ($p \leq 0.05$) in basil from the LED treatment compared to those in the other three treatments, which did not differ significantly ($p > 0.05$).

4 | DISCUSSION

Bibb lettuce and basil grown in aquaponics systems under LED lights both had higher average individual plant weights (g), higher plant production per unit area (g m^{-2}), and higher production per unit of energy (g m^{-2} kWh^{-1}) than those plants grown under FLO, MH, or IND lights. Plants utilize light spectra between 400 and 700 nm for

TABLE 5 Light spectra as a percentage of photosynthetically active radiation (PAR) and red to blue ratio (R:B) for four different types of plant grow lights

Light spectra (nm)	LED	MH	IND	FLO
400–499	22	39	22	87
500–599	13	47	29	8
600–699	64	11	33	5
700–799	0	3	16	0
R:B	2.85	0.28	1.50	0.02

Abbreviations: IND, induction; FLO, fluorescent; LED, light-emitting diode; MH, metal halide.

photosynthesis and growth. The total of wavelengths emitted by the light fixture within this region is known as the Photosynthetically Active Radiation (PAR). However, within PAR, the specific bands of wavelengths are also important. Light at frequencies from 400–499 nm (blue color) and 600–699 nm (red color) each target specific types of chlorophyll (chlorophyll b and chlorophyll a, respectively) within the plant tissue (Lin et al., 2013; Yeh & Chung, 2009). The percentage of PAR that each light emitted within these more specific bands of wavelengths is presented in Table 5.

An increase in overall plant weight and leaf surface area has been reported with lights producing increased red (Goins et al., 2001; Stutte et al., 2009) and far red (690–730 nm) wavelengths (Snowden et al., 2016). In the current study approximately 65% of the PAR produced by the LED lights was within the red-light spectra (600–699 nm), a much higher percentage than the other lights evaluated (Table 5). However, Yorio et al. (2001) reported that lights with 100% red spectrum did not perform as well as lights which contained 90% red (600–700 nm) and 10% blue (400–500 nm) for growing radish, spinach, and lettuce. Red and blue light are both important to different aspects of plant growth and the ratio of red light to blue light (R:B) is important for optimizing growth. This is supported by Kong et al. (2019) who found that LED lights with a R:B of 4.3:1 resulted in lettuce plants with 21% greater fresh weight than LED lights with a R:B of 1.7:1. Pennisi et al. (2019) reported that a R:B of 3:1 resulted in higher yields and improved nutritional quality of hydroponic sweet basil compared to other tested R:B ratios. The results in the current study support the findings of Pennisi et al. (2019) as the R:B ratio for the LED evaluated here was 2.9:1, compared to the R:B of MH (0.3:1), IND (1.5:1), and FLO (0.02:1). The FLO and MH lights utilized in this study had a higher proportion of blue and green (500–599 nm) wavelengths, suggesting that plant growth was reduced in these treatments due to reduced red spectra and appropriate R:B ratio.

In terms of energy use, FLO had the highest (4.6 avg kWh day^{-1}) while LED and IND lights had the lowest (3.4 avg kWh day^{-1}). Energy use by MH was intermediate (3.4 avg kWh day^{-1}). Daily electricity use of FLO was 18% greater than MH and 44% greater than LED and IND. However, when the different types of lights are compared in terms of plant productivity per unit of energy used, differences become much more pronounced. In Trial 1 with Bibb lettuce, LED produced 81% more plant weight per unit energy than IND, 151% more than FLO, and 160% more than MH. Differences in Trial 2 with basil were even larger, with LED producing 152% more plant weight per unit energy than IND, 219% more than MH, and 234% more than FLO. These results are in agreement with those of Oliver et al. (2018) for both Swiss chard (*Beta vulgaris*) and kale (*Brassica oleracea*). The economic impacts of these efficiencies will vary according to the electric power costs in the region of production.

Light quality has been reported to impact phytochemical and nutrient composition of horticulture crops (Chen et al., 2014; Kopsell et al., 2014; Li & Kubota, 2009). Nutrient analysis of Bibb lettuce (Table 2) and Basil (Table 4) in this study indicated several statistically significant differences among the light treatments; however, this difference could not be attributed to a specific light. The actual magnitudes of differences in leaf nutrient composition between lights was small and may not be of biological significance to the plant or the consumer.

Light-emitting diodes have distinct advantages over traditional grow lights including, custom spectrum output, cool operating temperatures, a long operating lifespan, and high photon output coupled with low energy use (Lin et al., 2013). Singh et al. (2015) reported that LEDs can produce similar yields to other light types, such as MH, while using as little as 25% of the energy. However, the cost of each fixture should not negate the potential energy savings. Total lighting costs for LEDs have been reported to be 2.3 times higher than traditional grow lights (Nelson & Bugbee, 2014). This is attributed to the high cost per fixture offsetting their lower operating costs. Bugbee (2017) calculated that an $800 LED grow light operated for 16 h day^{-1} (indoor plant production) would take approximately 5–10 years to recover the initial investment, assuming a $0.10 cost per kWh. This return-on-investment would likely be shorter if high value crops were grown or if the grower is able to get above market price for their produce. Despite the superior plant growth seen under the LED light used in this study, the high cost ($1400 per light) would likely not make them a feasible option for aquaponic practitioners growing leafy greens. Induction lights used here were priced the same as LED, whereas MH and FLO were $500 per light and $300 per light, respectively.

The applied research presented here provides practical information on crop production in aquaponics as it relates to light quality, which growers can use to select lighting that matches their budget. As LED technology improves, the ability to transfer focused radiation more efficiently to the plant canopy may result in fewer required fixtures and lower electricity requirements (Nelson & Bugbee, 2014). Future research using LEDs for plant production in aquaponics should concentrate on optimizing R:B ratio for specific crops (Meng et al., 2020) and evaluating low-cost LED lights to assist in economically feasibility of indoor aquaponic production.

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