Liquid Organic Fertilizer Effects on Growth and Biomass of Lettuce Grown in a Soilless Production System

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Abstract. Demand for locally produced, organically grown leafy greens is increasing throughout the United States. However, due to lack of efficient organic fertilizers (OFs) for soilless substrates, organic greenhouse production of leafy greens may be challenging. Therefore, a greenhouse study was conducted to analyze the effects of six liquid OFs on growth and development of lettuce in a soilless system. Two experiments were conducted using a randomized block design, and treatments included six fish- or plant-based OFs: OF₁ (5N–1P–1K), OF₂ (2N–5P–1K), OF₃ (3N–1P–1K), OF₄ (2N–2P–2K), OF₅ (4N–1P–1K), and OF₆ (3N–3P–2K); one inorganic fertilizer treatment (IF, 24N–8P–16K); and one unfertilized control treatment. Fertilizer solutions were prepared at 2 dS m^{−1} and applied at 100 mL/plant. In Expt. 1, fresh biomass for IF-treated plants was 12% to 38% greater than OF treatments, whereas this difference ranged from 25% to 57% in Expt. 2. Similarly, leaf area values of IF-treated plants were 5% to 40% greater than OF treatments in Expt. 1, and the difference ranged from 28% to 90% in Expt. 2. A possible explanation could be greater availability of nutrients in the IF treatment compared with OF treatments. There was no significant difference among fertilized treatments for number of leaves and stem diameter. Based on the index-based ranking, fish-based (OF₁) and fish- and plant-based (OF₂ and OF₆) performed well among different liquid OFs used in the study. Although the yield under OFs was less compared with that under IF, there is potential to reduce this yield gap by optimized fertility management of these fertilizers. Future research is needed to investigate the impact of optimized rate, timing, different placement, and additional nitrogen (N) sources of OFs on the soilless production of lettuce.

By providing biologically active substances such as vitamins, dietary fiber, antioxidants, and cholesterol-lowering compounds, vegetables play a vital role in human nutrition

(Hounsborne et al., 2008). Accordingly, a cultural shift toward healthier lifestyles and sustainable food production systems has emerged throughout the developed world (Reganold and Wachter, 2016). As a result, worldwide consumer demand for organic vegetables has increased significantly in recent years (Willer and Lernoud, 2019; Willer and Sahota, 2020; Willer et al., 2008). In addition, the number of operations producing organic vegetables has also increased. In the United States, sales and hectares for open-field conventional (nonorganic) vegetable production in 2017 were

\$19.6 billion and 1.6 million ha, respectively (Table 1). In comparison, open-field organic production sales and acreage for the previous year (2016) were \$1.64 billion and 0.075 million ha, respectively (Table 1). On a per-hectare basis, vegetable production from open organic systems had about two-times greater sales value than open conventional systems (Table 1). Similarly, covered systems such as greenhouses and high tunnels had significantly greater sales value than open systems regardless of type (organic vs. conventional) over the same time. For example, in 2015, covered organic vegetable systems had gross sales of \$534,321/ha compared with \$18,157/ha for open organic systems (Table 1).

The dietary guidelines for Americans recommend five servings of vegetables per day based on an intake of 2000 calories (Stewart and Hyman, 2019). It is also recommended one of the five servings of vegetables should be leafy green vegetables. One of the most used leafy green vegetables is lettuce (*Lactuca sativa* L.), a member of the sunflower family Asteraceae (Ryder, 1999). Today, lettuce is the most widely grown fresh vegetable in the United States (Ryder, 1999). Annually, per-capita lettuce consumption in the United States is ≈5.1 kg (Shahbandeh, 2021), which is five times greater than consumption a century ago. Lettuce is an excellent source of vitamin A, vitamin C, vitamin K, some B vitamins, and other phytonutrients (Kim et al., 2016). In addition, dark-green and red leaves of certain lettuce varieties provide a greater overall nutritional value when compared with varieties with lighter green leaves (Bunning and Kendall, 2012).

Greenhouse soilless cultivation of leafy greens has been shown to produce greater yields when compared with field cultivation on the basis of area under production (Greer and Diver, 2000). Greenhouse soilless production systems have been used to grow high-value and high-demand vegetable crops such as tomato (*Solanum lycopersicum* L.), cucumber (*Cucumis sativus* L.), bell pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.), and leafy greens [lettuce, arugula (*Eruca vesicaria* L.), spinach (*Spinacia oleracea* L.), kale (*Brassica oleracea* var. *sabellica* L.), and Swiss chard (*Beta vulgaris* ssp. *cicla* L.)] (Walters et al., 2020). These systems use organic potting mixes, or other inert media, for providing support to the plant (Greer and Diver, 2000). Because of the availability of little to no plant-available nutrients in inert media, leafy green producers face the challenge of providing adequate nutrients to plants, especially in organic production (Tittarelli, 2020). In addition, because plants in these systems grow very rapidly as a result of optimized growth conditions, synchronizing nutrient availability and nutrient demand becomes more critical in greenhouse production systems (Tei et al., 1996). Hence, proper selection of an OF source and media substrate (Rahman et al., 2019) is critical for providing the necessary nutrition to maintain production quality and yield standards in greenhouse soilless cultivation.

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Table 1. Production statistics for U.S. organic and conventional vegetable production systems.

Yr	Sales (\$)	ha	Sales (\$/ha)	Type
2017 ²	19,583,739,000	1,604,832	12,203	Open conventional
2012	16,851,235,000	1,691,948	9,960	Open conventional
2007	14,683,058,000	1,763,168	8,328	Open conventional
2002	12,785,898,000	1,389,396	9,202	Open conventional
2016	1,644,431,203	75,344	21,826	Open organic
2015	1,361,747,498	74,998	18,157	Open organic
2014	1,247,666,655	66,266	18,828	Open organic
2011	1,071,694,396	47,782	22,429	Open organic
2008	685,311,003	52,786	12,983	Open organic
2017	748,301,654	1,046	715,394	Covered conventional
2012	634,486,003	911	696,472	Covered conventional
2007	553,034,688	574	963,475	Covered conventional
2015	73,201,940	137	534,321	Covered organic
2014	75,857,306	182	416,798	Covered organic

²U.S. Department of Agriculture–National Agricultural Statistics Service (<https://www.nass.usda.gov/>).

In organic production, selection of plant and seed material, fertilizer sources, and pest management systems are governed by stringent, organic, certified cultural practices and guidelines issued by the U.S. Department of Agriculture. Therefore, the choice of fertilizer has to be from sources certified as organic by the Organic Material Review Institute (OMRI). Mostly, OFs from plant and animal sources such as blood meal, meat and bone meal, fish meal, seabird guano, chicken manure, poultry manure, and turkey manure are often used for in-ground (i.e., soil-based) organic vegetable production (Bi et al., 2010; Gaskell et al., 2007; Hartz and Johnstone, 2006). A significant challenge with organic residue-based fertilizers in soilless systems is nitrogen mineralization. Nitrogen mineralization affects the efficacy and timing of the nutrient supply to meet the demand of vegetable crops at critical stages of development (Treadwell et al., 2007), which in turn affects yield and quality of produce. Soil-based systems include microflora that facilitate mineralization of OFs. However, microflora are absent in soilless systems. Therefore, mineralization of OF sources in soilless systems are affected, and thus the bioavailability of nutrients to the plant is also reduced (Gaskell and Smith, 2007; Paillat et al., 2020). For this reason, use of OFs that do not require further mineralization is important for optimizing organic vegetable production under soilless greenhouse conditions (Bi et al., 2010).

Commercially available liquid OFs could fill this gap in providing adequate fertility to greenhouse-grown vegetables. Commercial liquid OFs are manufactured from various plant and animal residue wastes, such as fish hydrolysates, emulsions from seaweed and fish, and oilseed extract (Burnett et al., 2016).

These fertilizers are highly refined and concentrated forms developed by digesting animal- and plant-based organic waste at high temperatures, or by microbial digestion. Moreover, these liquid OFs contain plant-available macro- and micronutrients that may improve growth and yield of vegetables in organic soilless production systems. However, unlike IFs, research on the use of liquid OF in soilless greenhouse vegetable production is very limited (Treadwell et al., 2007). Within these contexts, the objective of our study was to evaluate the effect of six commercially available liquid OFs (derived from fish and plant sources) on growth and yield of butterhead lettuce cv. Rex grown in a soilless system under greenhouse conditions.

Materials and Methods

Experimental site and growth conditions.

Two experiments were conducted in a glasshouse at the horticulture gardens and greenhouse complex, Department of Plant and Soil Science, Texas Tech University, Lubbock, TX (lat. 33°35'03.3"N, long. 101°53'13.2"W; elevation, 979 m above mean sea level). Expt. 1 was conducted in the north portion of an east–west-oriented glasshouse from 6 Oct. to 24 Nov. 2019. Expt. 2 was conducted on the south side of the same glasshouse from 18 Nov. 2019 to 6 Jan. 2020. The average temperature inside the greenhouse for both experiments was 22 °C and an average humidity was 60%. The soilless substrate used in each experiment was Resilience Silicon Enriched Metro-Mix MM 902 RSi (Sun Gro Horticulture, Agawam, MA). Substrate consisted of 45% to 55% processed softwood

bark, 25% sphagnum peatmoss, 20% vermiculite, and 5% to 10% perlite.

Seed sowing and transplanting. Pelleted seeds of butterhead lettuce cv. Rex (Johnny's Selected Seeds, Winslow, ME) were sown into 72-cell plug trays (Hydrofarm, Petaluma, CA) on 6 Oct. and 18 Nov. 2019 in Expts. 1 and 2, respectively. Seedlings at the four-leaf stage were transplanted to 10-cm-diameter plastic (100-mL) pots filled with soilless substrate on 24 Oct. and 6 Dec. 2019 for Expts. 1 and 2, respectively.

Fertilizer treatments and their nutrient composition. Liquid OF treatments included OF₁ (5N–1P–1K), OF₂ (2N–5P–1K), OF₃ (3N–1P–1K), OF₄ (2N–2P–2K), OF₅ (4N–1P–1K), and OF₆ (3N–3P–2K) (Table 2). In addition, an IF (24N–8P–16K) and a no-fertilizer treatment/control (C) were included. All liquid OFs were listed under OMRI for organic crop production. Different sources and nutrient compositions of these OFs and IF are presented in Table 2. Each treatment was prepared in a 49-L-capacity plastic container by using reverse-osmosis (RO) water with a final electrical conductivity (EC) of 2.0 dS·m^{−1} (Orion Star A329 pH/ISE/Conductivity/Dissolved Oxygen Portable Multiparameter Meter; Thermo Fisher Scientific, Waltham, MA). The pH, EC, and total dissolved solids (TDS) of the prepared nutrient solution were measured before each application. On alternate days, respective fertilizer treatments and RO water were applied at 100 mL/plant. For the duration of each experiment, the control treatment received 100 mL of RO water every day.

Experimental design and data collection.

Experiments were a randomized complete block design with four replicates. There were six plants in each replication, and a total of 192 plants in each experiment. All pots were placed in a 9.0-m² area, with 20-cm spacing between plants. During the growing season, chlorophyll content was estimated (sixth leaf from plant center) from six plants from each replication at 7, 14, 21, and 28 d after transplanting (DAT) using a soil plant analysis development (SPAD) meter (Minolta SPAD 502 digital chlorophyll meter; Spectrum Technologies, Plainfield, IL). Chlorophyll concentration (measured in micromoles per square meter) was calculated using a methodology that converts SPAD values to micromoles per unit leaf area (Parry et al., 2014). At the end of each growing season, four plants from each replication were harvested, and yield parameters such as fresh biomass, number of leaves, total leaf area, stem diameter, and plant dry biomass were measured and calculated on a per-plant

Table 2. Organic and inorganic fertilizers used in our study at Lubbock, TX.

ID	Product name	Source	N–P–K	Biocomposition	Certification	Manufacturer
IF	Peter Professional	Inorganic	24N–8P–16K	Nitrate salts, urea	Synthetic	Peter Professional, Summerville, SC
OF ₁	Alaska fish fertilizer	Organic	5N–1P–1K	Fermented fish	OMRI listed	Lilly Miller, Atlanta, GA
OF ₂	Drammatic K fertilizer	Organic	2N–5P–1K	Fermented fish, kelp	OMRI listed	Dramm Corp, Manitowoc, WI
OF ₃	Nature's Source organic	Organic	3N–1P–1K	Fermented oilseed extract	OMRI listed	Nature's Source, Sherman, TX
OF ₄	Kellogg organic plus fertilizer	Organic	2N–2P–2K	Ocean fish, molasses, kelp	OMRI listed	Kellogg Garden, Carson, CA
OF ₅	SuperThrive organic fertilizer	Organic	4N–1P–1K	Fermented fish	OMRI listed	SuperThrive, Seekonk, MA
OF ₆	AgroThrive organic biofertilizer	Organic	3N–3P–2K	Fermented fish, grain	OMRI listed	AgroThrive, Gonzales, CA

ID = identification; OF = organic fertilizer; IF = inorganic fertilizer; OMRI = Organic Materials Review Institute.

Table 3. Performance rank versus cumulative rank index (RI) of the six organic fertilizers (OFs) compared with inorganic fertilizer in soilless lettuce (*Lactuca sativa* cv. Rex) greenhouse production at Lubbock, TX.

Treatment	Fresh biomass	Leaf No. of area	Dry leaves	RI
OF ₁	1	2	1	2
OF ₂	2	1	4	1
OF ₆	3	3	2	3
OF ₄	5	6	3	4
OF ₅	4	4	5	6
OF ₃	6	5	6	5

²Numbers in parentheses are the RI-based rank of each OF.

basis by dividing the total of each metric by four. Fresh biomass of a plant was recorded immediately after harvest using a weighing balance (Ohaus R31P15, Ranger 3000 Compact Bench Scale; Ohaus, Parsippany, NJ). The number of leaves from each plant was counted manually, and leaf area of was measured with a leaf area meter (LI-3100C; LI-COR, Lincoln, NE). The stem diameter of each plant was measured with digital caliper (Carrera Precision, Max Tool, Ontario, CA). To quantify dry biomass, plants were oven dried at 60 °C for 72 h and then weighed.

Index-based ranking. An index-based ranking was used for different OFs based on performance of the plant in each treatment compared with the IF treatment by data polling from both experiments (Table 3). Percentage change values (Supplemental Table 1) were used to assign performance ranks to each OF, with 1 point being the best performer and 6 points being the worst performer among all OFs (Table 3). Scores ranging from 1 to 6 points were assigned to each OF and added to determine the cumulative rank index (RI). The fertilizer treatment with the lowest RI was considered the best performer among OF treatments when compared with IF.

Statistical analysis. All data were analyzed statistically using the JMP statistical analysis software package (JMP, version 14.3; SAS Institute Inc., Cary, NC). Following a significant analysis of variance at $P < 0.05$, differences among treatment means were compared using the Tukey-Kramer honest significant difference test.

Results and Discussion

Greenhouse shading effects on lettuce growth during our study. Our production system involved conducting two experiments in a glasshouse with the glass roof positioned in an east–west direction, providing maximal sunlight in the greenhouse area. However, although the temperature was maintained at close to optimal levels, the lighting conditions were variable as a result of structural shading. The two experiments were both conducted during Fall and Winter 2019, and as such the sun angle differed to some degree for both experiments. As a result, the orientation of the greenhouse allowed for a shadow

to be cast over the area where the plants were situated. Expt. 1 was conducted in the north bay, where a significant amount of shading was present; Expt. 2 was conducted in the south bay, where there was significantly less shading. Although the plants were randomized in both iterations of our experiment, randomization was not sufficient to account for this shading. As such, the growth and development of the lettuce plants varied between Expt. 1 (24 Oct.–24 Nov. 2019) and Expt. 2 (6 Dec. 2019–6 Jan. 2020). Nonetheless, the two experiments were sufficient to assess the fertility capacity of the inorganic and organic formulations tested.

Leaf area and number of leaves. In each experiment, the leaf area of lettuce plants was greater in all OF treatments compared with the control treatment (Fig. 1A). However, in each experiment lettuce plants produced from IF treatments produced the greatest leaf area compared with all other treatments. Leaf area values of IF-treated plants were 5% and 40% greater than OF₂ (the greatest leaf area producer among OF treatments) and OF₃ (the lowest leaf area producer among OFs), respectively, in Expt. 1. Values were 28% and 90% greater than OF₁ (the greatest leaf area producer among OFs) and OF₄ (the lowest leaf area producer among OFs), respectively, in Expt. 2. Similar results were observed in a soilless greenhouse study conducted by Zandvakili et al. (2019). Researchers assessed the effects of OF solution on the growth and composition of lettuce, with a comparison of Hoagland and Arnon solution and no fertilization. Researchers observed the leaf area of different lettuce varieties grown with Hoagland and Arnon solution treatment were 184% and 537% greater than OF and unfertilized treatments, respectively. Although in our study differences in leaf area were present for all treatments across each experiment, OF₁, OF₂, and OF₆ (fish-based OFs) were consistent top performers among all OFs. Similar to these results, Ekinci et al. (2019) also reported the greatest leaf area in spinach when treated with fish manure in combination with IF. The possible reason for this could be fish fertilizer acts

as a good rooting media conditioner and helps in root development (Irshad et al., 2006), which increases nutrient uptake and leads to greater plant leaf area.

Similar to leaf area, number of leaves per plant were also greater in all OF treatments compared with the control treatment in Expts. 1 and 2. Although leaf area showed differences among fertilizer treatments, number of leaves per plant among IF and OF treatments were not different across Expts. 1 and 2 (Fig. 1B). Leaf number values of IF-treated plants were 3% and 11% greater than OF₁ (the greatest number of leaves among OFs) and OF₃ (the lowest number of leaves among OFs), respectively in Expt. 1, and the same values were 7% and 17% greater than OF₁ and OF₃, respectively, in Expt. 2. Similarly, Moncada et al. (2021) reported the greatest number of leaves of basil plants (*Ocimum basilicum* L.) under IF, and a progressive decrease with the increase in an OF component in the fertigation formula. The difference in growth (leaf area or leaf number) between IF and OFs can be attributed to differences in the availability of nutrients, especially N (Ellis and Foth, 1996). The lower nutrient availability in OFs for plant growth led to less growth and yield of lettuce compared with IFs. Moreover, the leaf number values of IF and OF₁ treatments were 187% and 174% greater than the control treatment, respectively, in Expt. 1, and the same values were 146% and 129% greater than the control, respectively, in Expt. 2. Therefore, data also indicate nutrient uptake of lettuce was effective under OF treatments and was comparable to that in IF treatment.

Stem diameter. In both experiments, the stem diameter of lettuce plants was larger in all fertilized treatments when compared with the control (Fig. 2A). The OF₄ treatment recorded the greatest stem diameter during each experiment. The stem diameter of lettuce in treatment OF₄ was 148% and 115% greater when compared with the control (treatment with smallest stem diameter) in Expts. 1 and 2, respectively. In Expt. 1, the stem diameter under OF₄ was greater (18%) than IF treatment, and all other OF treatments except OF₂.

Fig. 1. Butterhead lettuce (*Lactuca sativus* cv. Rex) leaf area (A) and number of leaves per plant (B) measured at 30 d after transplanting in Expt. 1 (E₁) and Expt. 2 (E₂) in Lubbock, TX. Box plots represent the mean $\pm$ SE of four replications. Box plots following the same letter in each experiment are not significantly different; lowercase letters are for E₁ and uppercase letters are for E₂. C = no fertilizer treatment; IF = inorganic fertilizer, OF = organic fertilizer.

Fig. 2. Butterhead lettuce (*Lactuca sativus* cv. Rex) stem diameter measured at 30 d after transplanting in Expt. 1 (E₁) and Expt. 2 (E₂) in Lubbock, TX. Box plots represent mean $\pm$ SE of four replications. Box plots following the same letter in each experiment are not significantly different; lowercase letters are for Expt. 1 and uppercase letters are for Expt. 2. C = no fertilizer treatment; IF = inorganic fertilizer, OF = organic fertilizer.

In addition to fish, both OF₄ and OF₂ included kelp in their fertilizer composition. As an OF, kelp is reported to increase the stem diameter of vegetables such as broccoli (*Brassica oleracea* var. *italica* L.) and cabbage (*B. oleracea* var. *capitata* L.) (Aldworth and Staden, 1987; Mattner et al., 2013). Furthermore, by enhancing the actions of growth regulators (particularly cytokinins, auxins, betaines, sterols, and organic polymers), in these studies kelp increased early plant growth and stem diameter (Craigie, 2011). In addition, Ali et al. (2021) reported seaweed-based products have phytostimulatory properties that help to increase plant growth and yield parameters such as stem diameter and leaf area. However, stem diameter was not different among OFs and IF treatments, but greater than the control treatment in Expt. 2 (Fig. 2A).

Chlorophyll content. The chlorophyll content of lettuce leaves in different fertilizer treatments followed a similar trend, with the peaks at 14 or 21 DAT for most fertilizer treatments in Expts. 1 and 2 (Fig. 3). The exception was OF₃ where chlorophyll content increased until 28 DAT in each experiment. The chlorophyll content of plant leaves is considered a very good abiotic stress indicator (drought or nutrient stresses) (Arunyanark et al., 2008). As growth of lettuce is exponential (Marcelis et al., 1998), growth from 2 weeks and onward is characterized by rapid growth and expansion of leaves (Shimizu et al., 2008). Thus, the decrease in chlorophyll across experiments and treatments at 28 DAT could be attributed to an insufficient supply of nutrients during this rapid stage of growth, or is merely a function of developmental age (de Sales et al., 2021). Also, the trend of chlorophyll accumulation was different for control plants, which exhibited a maximum chlorophyll content at 7 DAT, with subsequent declines at 14, 21, and 28 DAT in both Expts. 1 and 2. This can also be correlated to a decrease in chlorophyll content

Fig. 3. Butterhead lettuce (*Lactuca sativus* cv. Rex) chlorophyll concentration from Expt. 1 (A) and Expt. 2 (B). Bars represent the mean $\pm$ SE of four replications. C = no fertilizer treatment; DAT = days after treatment; IF = inorganic fertilizer, OF = organic fertilizer.

resulting from nutrient stress exhibited after 7 d because the control treatment was not supplied with any nutrients. Also, the chlorophyll content for the control treatment plants at 7 DAT was less than the chlorophyll content of plants undergoing fertilized treatments.

The chlorophyll content for leaves from fertilized treatments was greater on all sampling dates compared with the control treatment (Fig. 3). Our results are in agreement with research by Zandvakili et al. (2019), who reported greater SPAD readings from lettuce leaves from fertilized treatments compared with an unfertilized treatment. Madeira and Varennes (2005) concluded increased N fertilization in sweet pepper (*Capsicum annuum* L.) increased SPAD readings, total chlorophyll content, and leaf N concentration of young leaves. Dunn et al. (2018a) also reported that SPAD readings of poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) leaves had a correlation with N concentration. Chlorophyll accumulation is dependent on the availability of N within the media and the N uptake rate, and is therefore considered a good proxy for N status (Dunn et al., 2018a, 2018b; Oliveira et al., 2017). The differential performance in chlorophyll accumulation by several OF treatments indicates that N availability or uptake rate was affected by the N

source in each OF. Lettuce growth maximization requires that N levels be maintained above a critical value (Bottoms et al., 2012). Lettuce is a specialty crop that has stringent standards for quality that includes greenness, which is determined primarily by the chlorophyll content (Agüero et al., 2007; Kowalczyk et al., 2018). The timely delivery of N to a lettuce crop by OF requires a source of N where its bioavailability and uptake are not hindered. Therefore, OFs with a greater available N content could be beneficial for organic lettuce production.

Fresh and dry biomass. In each experiment, the fresh biomass of lettuce plants was greater in all OF treatments and IF treatment compared with control plants (Fig. 4A). The IF treatment recorded the greatest fresh weight during both experiments, whereas fresh biomass was different in all OF treatments only in Expt. 2. Fresh biomass for IF-treated plants was 12% and 38% greater than OF₂ (the greatest fresh biomass producer among OFs) and OF₃ (the lowest fresh biomass producer among OFs), respectively, in Expt. 1, and the same values were 25% and 57% greater than OF₁ (the greatest fresh biomass producer among OFs) and OF₄ (the lowest fresh biomass producer among OFs), respectively, in Expt. 2. The results for dry

Fig. 4. Butterhead lettuce (*Lactuca sativus* cv. Rex) fresh biomass (A) and dry biomass (B) measured at 30 d after transplanting in Expt. 1 (E₁) and Expt. 2 (E₂) in Lubbock, TX. Box plots represent the mean $\pm$ SE of four replications. Box plots following the same letter in each experiment are not significantly different; lowercase letters are for E₁ and uppercase letters are for E₂. C = no fertilizer treatment; IF = inorganic fertilizer, OF = organic fertilizer.

biomass exhibited similar trends as fresh biomass production, and OF treatments and the IF treatment produced greater dry biomass compared with the control (Fig. 4B). The dry biomass produced from the IF treatment was greater in each experiment, but only different from OF₃ and OF₅ in Expt. 1. In Expt. 2, the IF treatment was greater than OF₂, OF₃, OF₄, and OF₅. The dry biomass for IF-treated plants was 11% and 14% greater than OF₂ (the greatest dry biomass producer among OFs) and OF₃ (the lowest dry biomass producer among OFs), respectively, in Expt. 1, and the same values were 10% and 23% greater than OF₁ (the greatest dry biomass producer among OFs) and OF₄ (the lowest dry biomass producer among OFs), respectively, in Expt. 2.

In our study, fresh biomass results for both IF and OF treatments were comparable to previous studies (Singh et al., 2019). Zandvakili et al. (2019) reported the fresh weight of lettuce increased with IF treatment, which was 67% greater than the OF treatment, and 90% greater than the unfertilized treatment. Compared with the unfertilized treatment, lettuce fresh weight improved by 72% with organic fertilization. The authors explained the increased fresh weight of lettuce was the result of readily available nutrients in the IF treatment compared with organic and unfertilized treatments (Zandvakili et al., 2019). An additional greenhouse study concluded fresh biomass of sweet basil was the greatest in a conventional fertilizer treatment (250 kg·ha⁻¹ N) followed by an OF treatment applied at 150 kg·ha⁻¹ N compared with 150 kg·ha⁻¹ N of conventional and 250 kg·ha⁻¹ N OF treatments (Bufalo et al., 2015). The conventional inorganic treatment (250 kg·ha⁻¹ N), increased the fresh weight yield of sweet basil by 62% compared with the 150 kg·ha⁻¹ N OF treatment. In our study, similar results were found; the IF treatment resulted in greater fresh biomass compared with OFs and the control in each experiment. However, our results are in contrast with those of Drăghici et al. (2016), who reported lettuce plant fresh biomass was greater with one of the liquid organic fertilizer treatments (total N, 82.2 g·L⁻¹) compared with a chemical fertilizer treatment (total N, 23 g·L⁻¹) using the nutrient film technique. In their study, the researchers found that the greater nutrient rate of the organic fertilizer increased the fresh biomass of lettuce.

Similar to fresh biomass, results for dry biomass production under both IF and OF treatments in our study were in agreement with previous reports. For example, Bufalo et al. (2015) reported the dry biomass of sweet basil was 88% greater with the 250 kg·ha⁻¹ N conventional fertilizer treatment compared with the 150 kg·ha⁻¹ N organic fertilizer treatment. Biomass accumulation in lettuce production is a direct result of fertility management, which includes fertilizer type, rate, and timing of application (Ahmad et al., 2016). Indeed, optimal fertility requires precise synchronization of nutrient bioavailability and demand, especially during rapid periods of growth (Gaskell

and Smith, 2007; Treadwell et al., 2007). Although OF treatments in our study demonstrated reductions in biomass and yield compared with IF, the yield differences among OF and IF treatments could be reduced by optimizing fertility management variables (rate and timing), and by selection of suitable media substrates (Paillat et al., 2020).

Index-based ranking of organic fertilizers. The growth and yield results presented indicate variability in the effectiveness of each OF to provide sufficient nutrition for supporting positive growth of lettuce plants. Although growth in Expt. 1 was less than Expt. 2, relative differences among OFs were similar such that a determination of rank could be made. Results indicate RI for six OFs (Table 3) correlated well with the performance of each OF, as assessed by percentage yield reductions (Supplemental Table 1). Our results indicate fish-based (OF₁) and fish- and plant-based (OF₂ and OF₆) liquid OFs could be used in organic greenhouse lettuce production with proper optimization of rate and timing. The possible reason for an outstanding performance of OF₁ could be the greater N content found in OF₁ compared with other fish-based OFs used in our study. The better performance of OF₂ and OF₆ may be attributed to the greater phosphorus (P) and potassium (K) content in their composition. OF₂ had a lower number of leaves compared with OF₆, but OF₂ was ranked greater than OF₆ because of its greater fresh and dry biomass. This is likely a result of greater P concentrations in OF₂, and OF₂ plants had thicker stems resulting in greater fresh and dry biomass compared with OF₆ plants. Previous research conducted by Soundy et al. (2001) also reported the stem diameter of lettuce increased quadratically with greater P fertilization. Therefore, we can deduce OFs should contain adequate amounts of N, P, and K for supporting growth and development of lettuce in organic soilless production systems.

Conclusion

Use of OFs for soilless production of lettuce decreased all yield parameters (fresh biomass, dry biomass, number of leaves, leaf area) compared with plants grown using the under the IF treatment. Stem thickness was the only growth parameter that was greater with one of the tested OFs (OF₄) compared with the IF treatment. However, lettuce yield grown with OFs was greater than the control treatment. Chlorophyll content was greater in fertilized treatments (IF and OFs) compared with the unfertilized control plants. Based on the index-based ranking, fish-based (OF₁) and fish-cum-plant-based (OF₂ and OF₆ fertilizers) performed better in comparison with different liquid OFs used in our study. Although yield with OFs was less compared with that under IF, there is a potential to reduce this yield gap by optimized fertility management of these fertilizers. Therefore, future research is needed to investigate the optimized rate, timing, and different placements

of these OFs, and the impact OF fertilizers have on soilless production of lettuce.

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Supplemental Table 1. Butterhead lettuce (*Lactuca sativus* cv. Rex) growth parameter percentage change represented by data pooled from Expts. 1 and 2 using organic fertilizers and no fertilizer compared to inorganic fertilizer treatment at Lubbock, TX.

Treatment	Fresh biomass	Leaf area	No. of leaves	Dry biomass
OF ₁	-17.5	-19.2	-4.5	-9.2
OF ₂	-18.7	-15.5	-8.6	-9.0
OF ₃	-29.7	-30.2	-11.8	-14.6
OF ₄	-25.4	-34.9	-8.1	-12.9
OF ₅	-23.7	-24.8	-9.8	-14.9
OF ₆	-21.7	-23.3	-7.3	-10.7
Control	-94.8	-95.4	-62.0	-65.0

OF = organic fertilizer.