HORTSCIENCE 60(9):1592–1598. 2025. https://doi.org/10.21273/HORTSCI18652-25

Effects of Two Planting Densities on Leafy and Fruiting Crops in Aquaponic Hoophouse Production

Teal Hendrickson and Bruce L. Dunn

Department of Horticulture and Landscape Architecture, Oklahoma State University, 320G Agricultural Hall, Stillwater, OK 74078-6027, USA

Keywords. banana pepper, bluegill, cilantro, kale, pole bean

Abstract. **Aquaponics, the practice of growing fish and plants in the same system, has become increasingly popular as a solution to food scarcity, especially in urban areas. However, most current research is focused on fish rearing or growth of plants. Our research focused on planting density for two leafy plants, kale (*Brassica oleracea* L.) and cilantro (*Coriandrum sativum* L.), and two fruiting plants, banana peppers (*Capsicum annuum* L.) and pole beans (*Phaseolus vulgaris* L.), at high (30, 37, 12, and 14 plants/m^2) and low (20, 26, 6, and 7 plants/m^2) planting densities, respectively. Six aquaponic systems were set up in a hoophouse in Stillwater, OK, USA, and stocked with bluegill (*Lepomis macrochirus* L.) fingerlings. All crops were found to have a greater vegetative biomass at lower planting densities, as well as greater chlorophyll content in all plants except banana peppers. Number and weight of fruit did not change significantly between planting densities, but peppers were longer at greater densities.**

Modern problems often require modern solutions, but lack of land, or degradation of previously arable land, has transcended time as civilization has expanded (Prăvălie et al. 2021). Approximately 40% of all arable land is experiencing some form of degradation, usually via soil erosion, with urban centers constantly expanding and reducing agricultural land (Prăvălie et al. 2021; Shi et al. 2016). Urban expansion into rural areas, also known as urban creep, has been increasing in recent years as urban populations rise and developing nations grow (Mohammadi et al. 2021; Pandey and Seto 2015; Parsipour et al. 2019). Urban creep affects most countries, progressing more rapidly in developing nations, and requires solutions to protect agricultural land and integrate agriculture into urban areas (Parsipour et al. 2019). As more than 309 million people globally are facing acute food scarcity, integrating agriculture into urban landscapes has become more important than ever (World Bank 2022; World Food Programme 2023). Aquaponics, the combination of aquaculture and hydroponics, may be part of the integration solution.

Use of aquaponic systems dates to 1000 A.D., when the Aztecs conquered their lack of land by covering rafts in soil, planting crops, and suspending the rafts in ponds and lakes (Jones 2002; Okomoda et al. 2023). Modern aquaponic systems can be used in many locations because of their low land requirements beyond electricity and limited fresh water, especially in "unusable" potential agricultural landscapes, such as urban areas and poor agricultural land (El-Essawy et al. 2019). Although aquaponic systems have been used previously, primarily in greenhouse settings, use of these systems without a controlled environment is possible in many locations, such as outdoors in favorable climates, hoophouses, and rooftops (Love et al. 2015). In a study using a geographic information system-based multi-criteria decision analysis to determine ideal location for aquaponics utilization, Zaniboni et al. (2024) found that the most favorable locations for aquaponics were around principal cities, suggesting that aquaponics could be incorporated into urban creep.

In addition, unlike in traditional field agriculture and many hydroponic growing systems, aquaponic systems use a closed recirculating system, producing minimal amounts of wastewater and promoting long-term sustainability and limited runoff in urban areas. In fact, aquaponic systems may improve water use by 85% and produce 100% to 150% more plant matter compared with traditional field agriculture (AlShrouf 2017). Not only can aquaponic systems produce all-organic, nutritious leafy greens and fruit, but also they produce fish, a commonly consumed protein by most individuals and cultures, suiting the diversity found in urban centers (Clark and Tilman 2017). However, scant research has been done to improve grower recommendations for plants in aquaponics, leaving a dearth of knowledge for prospective business owners and growers.

One such realm is planting density for various types of aquaponic crops. Planting density, the number and spacing of plants in a specified area, is as important as fish stocking rate, as plants remove the nitrates from the cycling water, purifying the water for the aquatic species used (Boxman et al. 2017). Most planting densities found in the literature are based on personal experience, traditional field agricultural standards, or fish stocking rate (Pickens et al. 2016; Somerville et al. 2014; Surnar et al. 2015). However, as a result of the increases in nutrients provided by fish waste fertilizer, the possibility of increasing planting density may provide a novel opportunity to produce more crops in less space.

Current recommendations are conflicting, as each experiment uses a different planting density. Surnar et al. (2015), citing experience, suggested that 12 plants/m^2 was the appropriate density for spinach (*Spinacia oleracea* L.) and tomato (*Solanum lycopersicum* L.) in a 6 m^2 grow bed, whereas Pickens et al. (2016) recommended densities of 24.2 plants/m^2 for leafy crops and 4 plants/m^2 for vining crops. Conversely, Afolabi (2020) stocked kale at density of 25 plants/m^2 in a comparison study of deep-water culture vs. integrated aquavegeculture, and Ani et al. (2022) used 16 plants/m^2 for a fish density trial using lettuce (*Lactuca sativa* L.) as the representative plant. Baßmann et al. (2020) found that greater densities of basil influenced African catfish (*Clarias gariepinus* L.) welfare and behavior positively, whereas greater densities (144 plants) of basil (*Ocimum basilicum* L.) had 1.7% less leaf area than lower densities (n = 48) in 1.5 m^2 grow areas, but Boxman et al. (2017) found that planting density did not affect plant growth in a marine aquaponic system. In a technical article by Somerville et al. (2014), densities for 12 different plants are given; however, there is no reasoning given behind the recommendations. No commonly accepted standards for planting density in aquaponic grow beds exist, leaving those interested in aquaponic systems to guess at guidelines for planting. This study sought to examine two densities of several vegetable and herb species to provide recommendations of plant density in aquaponic systems.

Materials and Methods

This experiment took place at the Botanic Garden at Oklahoma State University in Stillwater, OK, USA, in a hoophouse on the premises. Six identical aquaponic systems (20 EXT Aquaponic System; Symbiotic Aquaponic, McAlester, OK, USA) were purchased. Each system had a 492.1 L fish tank, 1.9 m^2 media bed grow space, and a 30 L·min^{-1} flow rate. Tanks were stocked with 45 bluegill (*Lepomis macrochirus* L.) fingerlings (Moore's Fish Farm, Inola, OK, USA) each, and fish were replaced or culled as needed to correct for death and illness. After 8 months of growth, bluegill fish were culled to half their population to prevent overcrowding. Bluegill fish were weighed at the beginning and end of each plant growth cycle, and fish reaching 0.45 kg were harvested at the end of each cycle. Fish were fed to satiation with 1.5 mm floating pellets with 40% crude protein (Optimal Fish Food, Omaha,

Received for publication 11 Apr 2025. Accepted for publication 3 Jul 2025.
Published online 26 Aug 2025.
T.H. is the corresponding author. E-mail: teal.hendrickson@okstate.edu.

NE, USA) two to four times a day (John and Mahalingam 2021) based on age.

Four species of plants were evaluated for crop density in these systems: kale (*Brassica oleracea* var. *acephala* L. 'Winterbor'), cilantro (*Coriandrum sativum* L. 'Cruiser'), banana pepper (*Capsicum annuum* L. var. Goddess F1), and pole beans (*Phaseolus vulgaris* L. 'Seychelles OG') (Johnny's Seeds, Winslow, ME, USA). Two densities of planting were chosen, with high densities being comprised of double the field planting recommendations with 54 kale plants, 68 cilantro plants, 14 pepper plants, and 22 pole bean plants (30, 37, 12, and 14 plants/m^2 respectively), whereas low densities were comprised of current field planting recommendations with 36 kale plants, 48 cilantro plants, 7 pepper plants, and 11 pole bean plants (20, 26, 6, and 7 plants/m^2 respectively). Kale and cilantro cultivars were planted in 2.5 cm rockwool cubes, whereas peppers and beans were planted in 3.8 cm rockwool cubes (Grodan, Roermond, Netherlands).

Each density of plants was repeated in two beds per replication for a total of two repetitions for each plant species per replication. Each plant species was planted sequentially for a total of two replications over time per plant species. Kale and cilantro were grown over winter in the first year, and pepper and beans were grown over the summers of the first and second years of growing.

The average temperature during the course of the experiment was 10.4 ± 8.2 and 20.5 ± 12.9 °C for kale, 23.6 ± 14.0 and 25.0 ± 11.7 °C for cilantro, 31.8 ± 9.5 and 25.2 ± 10.6 °C for peppers, and 17.9 ± 9.2 and 21.6 ± 11.7 °C for beans. Relative humidity averaged 34.9 ± 15.5 and 49.9 ± 15.6% for kale, 35.5 ± 20.3 and 43.6 ± 23.1% for cilantro, 40.9 ± 21.5 and 37.3 ± 20.7% for peppers, and 46.0 ± 23.5 and 26.7 ± 24.4% for beans. Daily light integrals averaged 5.7 ± 7.6 and 11.2 ± 19.7 $mol \cdot m^{-2} \cdot d^{-1}$ for kale, 24.0 ± 25.3 and 18.6 ± 21.6 $mol \cdot m^{-2} \cdot d^{-1}$ for cilantro, 20.6 ± 14.6 and 21.3 ± 18.3 $mol \cdot m^{-2} \cdot d^{-1}$ for peppers, and 17.3 ± 27.0 and 18.6 ± 23.1 $mol \cdot m^{-2} \cdot d^{-1}$ for beans.

Data collection. Water pH, electrical conductivity (EC), and temperature were measured daily using a portable pH/EC/temperature meter (Hanna Instruments, Smithfield, RI, USA). Ammonia, nitrite, and nitrate levels were measured weekly (API Test Kit; Aquarium Pharmaceuticals Inc. McLean, VA, USA). All water quality parameters were kept within recommended ranges using water changes, pH up powder (Symbiotic Aquaponic), and General Hydroponics pH Down Liquid (Hawthorne Hydroponics, Tyler, TX, USA) (Tables 1 and 2, Figs. 1–3). Supplemental chelated iron (Symbiotic Aquaponic) was added as needed.

Height, dry weight, and total dry root biomass were taken for each plant after 7 weeks of growth for kale and 6 weeks of growth for cilantro. Height was taken on four representative plants each week during the course of the growing cycle. In addition, chlorophyll was measured using a soil plant analysis development (SPAD) meter (SPAD-502; Konica Minolta, Tokyo, Japan) at the end of the growing period. Two SPAD readings were taken from each kale and cilantro plant, one from an inner leaf and one from an outer leaf. Readings were averaged to determine the chlorophyll concentration. Fresh foliar rate and Brix readings, using a handheld refractometer (Sungrow, Carrollton, TX, USA), were taken at the end of the growth period for kale and cilantro. Shoot and root samples were dried at 59 °C for 1 week.

Table 1. Nutrients found in water samples taken at the end of each growing cycle for two densities grown in aquaponic systems in a hoophouse in Stillwater, OK, USA.

	Plant density		
Nutrient (ppm)	High	Low	*P* value[i]
Sodium	170.3 a[ii]	194.3 a	0.5737
Potassium	25.6 a	21.9 a	0.5238
Calcium	50.6 a	51.2 a	0.8615
Magnesium	48.3 a	49.9 a	0.7509
Chloride	161.8 a	186.1 a	0.5141
Boron	0.36 a	0.39 a	0.5690
Nitrate-nitrogen	17.2 a	15.8 a	0.7901
Sulfate	230.8 a	255.5 a	0.6344
Bicarbonate	143.5 a	139.6 a	0.8776
Zinc	0.8 a	0.8 a	0.9178
Iron	1.8 a	2.1 a	0.6026

[i] All *P* values are nonsignificant.
[ii] Means within a row followed by same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).

Height, fresh weight, dry weight, and total dry root weight were taken for each plant after 13 weeks of growth for peppers and 10 weeks of growth for beans. Fruit were harvested, weighed, and measured each week for 5 weeks for peppers and beans, and Brix measurements were taken for each fruit harvested using the refractometer. In addition, chlorophyll was measured using the SPAD meter at the end of the growing period. Three SPAD readings were taken from each pepper and bean plant on a top, middle, and bottom leaf. Readings were averaged to determine the chlorophyll concentration. Shoot and root samples were dried at 59 °C for 1 week.

Three dried samples comprised of four plants each were chosen randomly to be analyzed for nutrients. Water samples were collected from the fish tank, sump tank, and grow bed after each replication. Both the dried samples and water samples were then sent to the Soil, Water and Forage Analytical Laboratory at Oklahoma State University (Stillwater, OK, USA) for analysis of leaf mineral element concentrations and water nutrients using a nutrient analyzer (TruSpec Carbon and Nitrogen Analyzer; LECO Corp., St. Joseph, MI, USA).

Statistical analysis. The study was a randomized complete block design with two replications per plant species, blocking for repetition and planting date. Water quality data were treated as a randomized complete block design with two replications per plant species and were blocked for repetition to compare water quality at differing densities. Statistical analysis was performed using SAS/STAT software (version 9.4; SAS Institute, Cary, NC, USA). Tests of significance were reported at the 0.05 level. Data were analyzed using generalized linear mixed-models methods, with Tukey's multiple comparison methods used to separate the means.

Results and Discussion

Water quality parameters. No significant differences in water quality parameters were observed between the two planting densities for any crop (Tables 1–3, Figs. 1 and 2).

Planting density effects on plant growth. All crops showed an increase in individual plant biomass at low densities compared with high densities (Table 4). Bennett et al. (2013) found that lower planting densities (6.7 plants/m^2 compared with 10 and 25 plants/m^2) impacted overall vegetative growth positively as a result of a reduction in resource competition. Naiki and Gupta (2010) found that lower planting density and more space between plants increased leaf weight and overall plant, but not yield per plot, and Singh et al. (2003) found similar results in kohlrabi (*Brassica oleracea* var. *gongylodes* L.). Although the stem diameter and stem-to-leaf ratio were greater as space between plants increased, overall yield tended to decrease as spacing increased (Patil et al. 2003; Singh et al. 2003). Nasto et al. (2009) found that pepper (*C. annuum* L. var. Gogozhare) plants had greater fresh weight at 11.1 plants/m^2 compared with 2.6 plants/m^2. Likewise, Ahmad et al. (2021) found that denser planting (60 × 30 cm) of sweet banana pepper (*C. annuum* L.) increased fresh weight, and therefore dry weight, of pepper plants.

Table 2. Water quality properties found in samples taken at the end of each growing cycle for two densities grown in aquaponic systems in a hoophouse in Stillwater, OK, USA.

	Plant density		
Water quality property	High	Low	*P* value[i]
Total dissolved solids (ppm)	935.2 a[ii]	992.4 a	0.6653
Potassium absorption ratio	0.36 a	0.31 a	0.5167
Sodium absorption ratio	4.0 a	4.5 a	0.5767
Exchangeable potassium (%)	6.9 a	6.4 a	0.5029
Exchangeable sodium (%)	4.4 a	4.9 a	0.5941
Hardness (ppm)	324.1 a	332.8 a	0.7573
Alkalinity (ppm)	119.2 a	115.4 a	0.8629

[i] All *P* values are nonsignificant.
[ii] Means within a row followed by the same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).

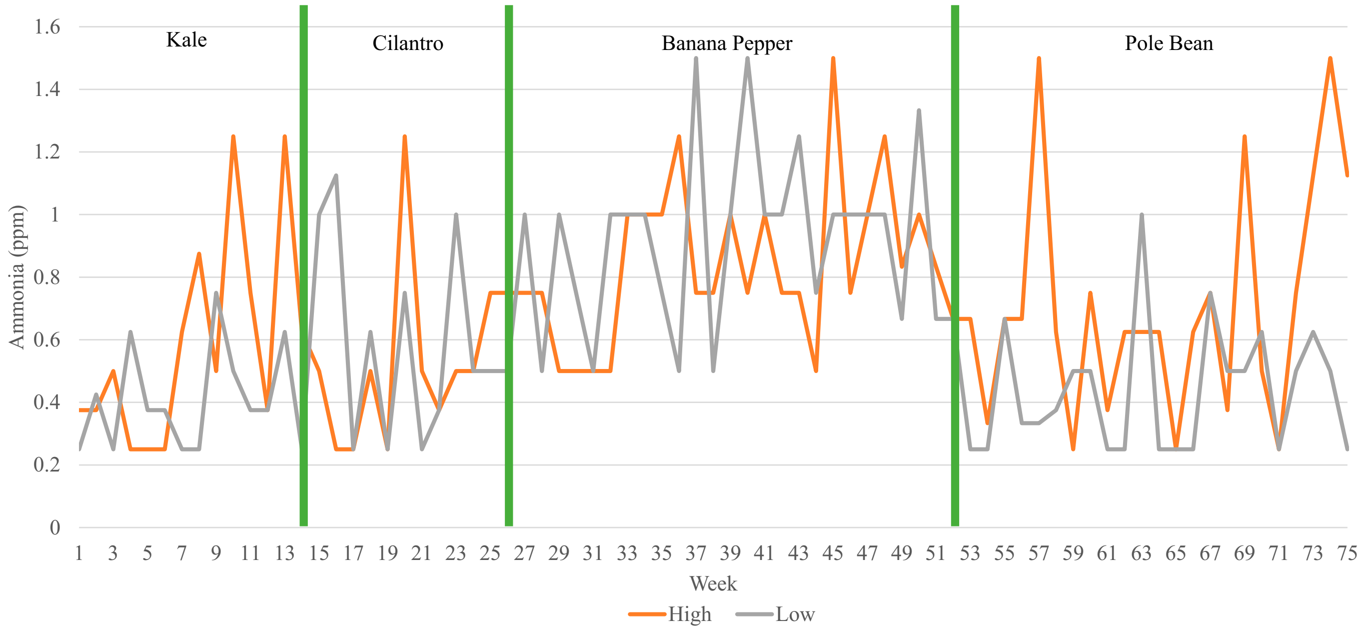

Fig. 1. Weekly average ammonia levels in aquaponic systems planted with two different densities of four crops (kale, cilantro, banana peppers, and pole beans) over time in a hoophouse in Stillwater, OK, USA.

Both cilantro and pepper plants were taller at greater planting densities than at lower planting densities (Table 4). Ahmad et al. (2021) found that denser planting (60 × 30 cm) of sweet banana pepper produced taller plants than the 60 × 60 cm spacing, as did Nasto et al. (2009). Conversely, Aminifard et al. (2012) observed that sweet pepper height decreased with increased planting density. Paprika peppers also decreased in height as plant spacing decreased (Aminifard et al. 2010). Conversely, many previous studies on planting density in cilantro showed no significant effect or a decrease in height at greater planting densities (Kahn and Maness 2010; Li et al. 2024; Painkara et al. 2024). However, Mangan et al. (2001) found that cilantro planted at greater densities increased in height, similar to our study. Although competition for nutrients can decrease growth, competition for light can cause plant plasticity, leading to more allocations for plant growth to out-shade nearby competition (Xiao et al. 2006).

Kale, cilantro, and pole beans had greater SPAD values, leading to a greater chlorophyll content at the lower planting density (Table 4). Although in some plant species, such as certain varieties of rice (*Oryza sativa* L.), plant density does not affect chlorophyll content, both kale and cilantro have been shown previously to experience an increase in chlorophyll content as plant spacing increases (Arjona 1980; Mondal et al. 2013; Naiki and Gupta 2010; Sharma et al. 2016). Arjona (1980) found that, as kale was spaced from 22 to 30 cm, chlorophyll content increased significantly, whereas additional spacing did not increase chlorophyll content. Noboa et al. (2022) measured comparable SPAD values, as increasing hydroponic row spacing allowed for an increase in chlorophyll content. Similarly, Naiki and Gupta (2010) found that increasing spacing from 30 × 20 cm to 30 × 40 cm produced kale with a greater chlorophyll content. Sharma et al. (2016) found that increasing spacing, thus decreasing planting density, improved yield and other quality parameters, such as chlorophyll content, in cilantro, likely as a result of increased space

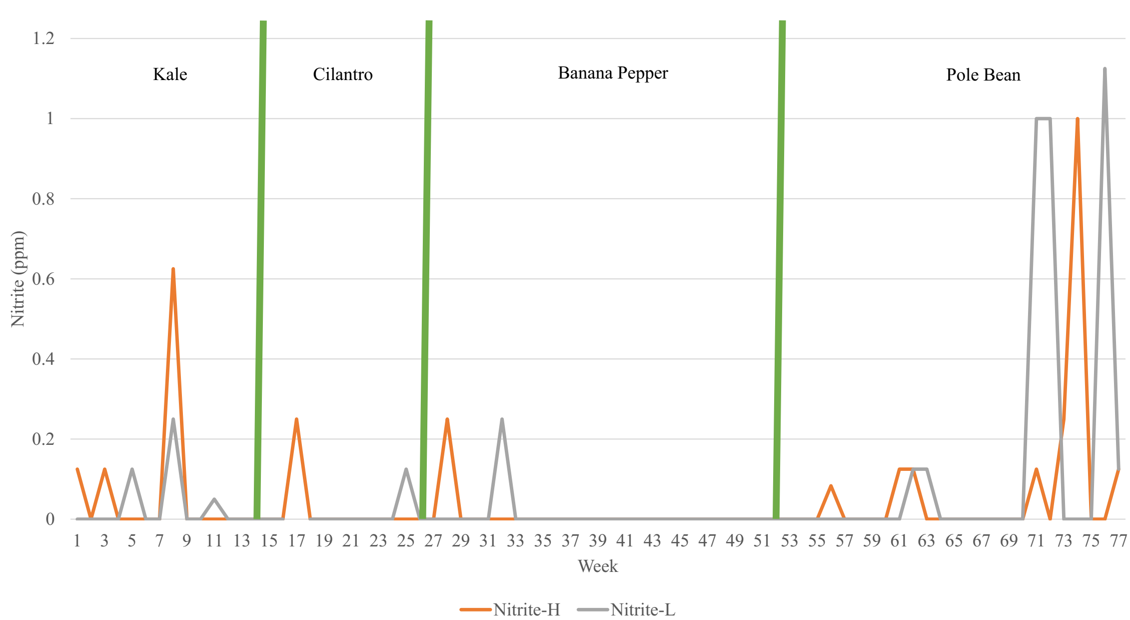

Fig. 2. Weekly average nitrite levels in aquaponic systems planted with two different densities of four crops (kale, cilantro, banana peppers, and pole beans) over time in a hoophouse in Stillwater, OK, USA.

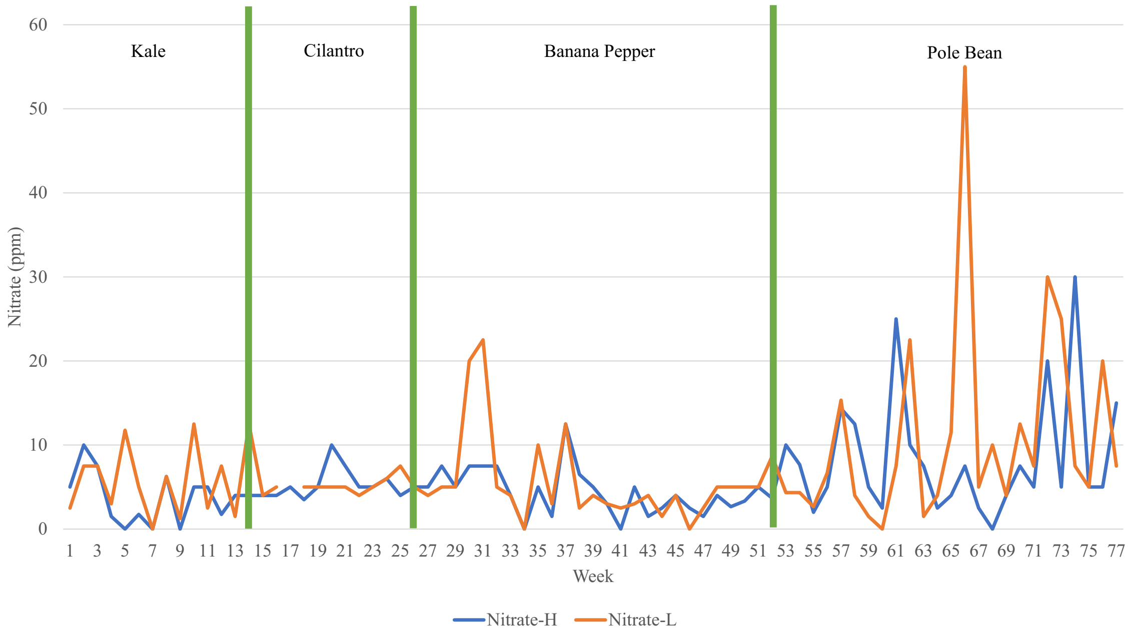

Fig. 3. Weekly average nitrate levels in aquaponic systems planted with two different densities of four crops (kale, cilantro, banana peppers, and pole beans) over time in a hoophouse in Stillwater, OK, USA.

Table 3. Weekly water quality parameters taken on aquaponic systems planted with different densities over the course of eight growing cycles in Stillwater, OK, USA.

	Plant density			
Water quality parameter	High	Low	Recommended range	P value[i]
Daily temperature (°C)	22.2 a[ii]	21.7 a	26–32[iii]	0.0727
Daily pH	7.9 a	7.9 a	6.5–8.5	0.4566
Daily electrical conductivity (ms·cm^{-1})	0.9 a	1.0 a	0.205[iv]	0.3125
Weekly ammonia (ppm)	0.7 a	0.6 a	<8.0	0.1443
Weekly nitrite (ppm)	0.0 a	0.1 a	<1.0[v]	0.6044
Weekly nitrate (ppm)	5.8 a	7.4 a	<250.0	0.1626

[i] All P values are nonsignificant.
[ii] Means within a row followed by the same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).
[iii] Recommended ranges for temperature, pH, ammonia, nitrite, and nitrate derived from Akinwole and Adeola (2012).
[iv] Recommended range for electrical conductivity by Stone et al. (2013).
[v] Recommended range for nitrite by Bhatnagar and Pooja (2013).

allowing for abundant vegetative control. Increases in chlorophyll content with lower planting density are likely a result of shading competition in tightly spaced plants (Arjona 1980). In addition, increases in chlorophyll content may also be the result of a greater availability of water, nutrients, and sunlight, and an overall reduction in competition (Naiki and Gupta 2010).

Planting density effects on nutrient content of kale, pepper, and bean plants. Although most secondary and micronutrients were not found to be significantly different in any plant species at either planting density, kale showed a significant difference in sulfur content between the high and low planting densities (Table 5). *Brassica* species are known for high levels of secondary sulfur compounds,

Table 4. Main effects of planting density on the physical characteristics of four crops in aquaponic systems stocked with bluegill in Stillwater, OK, USA.

Plant species and density	Fresh shoot wt (g)	Dry shoot wt (g)	SPAD	Height (cm)	Total root biomass (g)	°Brix
Kale						
30 plants/m^2	71.8 b[i]	6.8 b	42.7 b	25.8 a	193.0 a	7.1 a
20 plants/m^2	90.5 a	8.5 a	44.3 a	26.0 a	166.2 a	6.7 a
P value	0.0031**	0.0069**	0.0044**	0.7211^{NS}	0.6138^{NS}	0.0620^{NS}
Cilantro						
37 plants/m^2	59.3 b	4.3 a	37.1 b	31.1 a	663.3 a	4.2 a
26 plants/m^2	69.8 a	5.6 b	38.7 a	29.6 b	685.8 a	4.5 a
P value	0.0173*	0.0004***	<0.0001***	0.0330*	0.9371^{NS}	0.0848^{NS}
Pepper						
8 plants/m^2	—[ii]	100.2 b	50.8 a	101.2 a	912.6 a	—
4 plants/m^2	—	127.4 a	52.7 a	91.3 b	353.2 a	—
P value	—	0.0139**	0.1023^{NS}	0.0477*	0.3136^{NS}	—
Bean						
12 plants/m^2	—	71.3 b	38.8 b	179.8 a	147.3 a	—
6 plants/m^2	—	110.4 a	41.7 a	201.9 a	547.2 a	—
P value	—	0.0309*	0.0068**	0.1137^{NS}	0.1944^{NS}	—

[i] Means within a column followed by the same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).
[ii] Data not collected on nonedible plant parts.
NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.
SPAD = soil plant analysis development.

Table 5. Foliar nutrient contents of four crops grown in aquaponic systems in Stillwater, OK, USA at two different planting densities.

Plant species and density	Total nitrogen (%)	Phosphorus (%)	Potassium (%)	Magnesium (%)	Calcium (%)	Sulfur (%)
Kale						
30 plants/m^2	5.4 a[i]	0.7 a	4.6 a	0.6 a	3.0 a	1.3 a
20 plants/m^2	5.6 a	0.7 a	4.8 a	0.5 a	3.0 a	1.2 b
P value	0.2308^{NS}	0.2469^{NS}	0.1869^{NS}	0.1065^{NS}	0.7322^{NS}	0.0025***
Cilantro						
37 plants/m^2	5.3 a	1.1 a	8.9 a	0.6 a	1.4 a	0.3 a
26 plants/m^2	5.3 a	1.1 a	8.8 a	0.6 a	1.4 a	0.3 a
P value	0.7369^{NS}	0.3700^{NS}	0.8902^{NS}	0.2620^{NS}	0.6398^{NS}	0.8677^{NS}
Pepper						
8 plants/m^2	3.9 a	0.4 a	6.5 a	1.0 a	1.3 a	0.5 a
4 plants/m^2	4.0 a	0.4 a	5.5 b	1.0 a	1.4 a	0.5 a
P value	0.5392^{NS}	0.4003^{NS}	0.0341*	0.8744^{NS}	0.2799^{NS}	0.5716^{NS}
Bean						
12 plants/m^2	2.4 b	0.5 a	2.9 b	0.9 a	2.0 a	0.2 b
6 plants/m^2	2.9 a	0.5 a	3.3 a	1.0 a	2.0 a	0.2 a
P value	0.0163**	0.5612^{NS}	0.0454*	0.5326^{NS}	0.9033^{NS}	0.0192**

[i]Means within a column followed by the same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).
NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

such as glucosinolates (Aghajanzadehdivaei 2015). Nasiri et al. (2017) found that canola (*Brassica napus* L.) cultivars increased in glucosinolates as planting density increased from 40 to 80 plants/m^2. Similarly, Phong et al. (2019) found that glucosinolates were greatest in watercress (*Nasturtium officinale* L.; Brassicaceae) on day 35 of growth when plants were spaced at 14 cm compared with 20 and 30 cm planting densities. Chishaki and Horiguchi (1997) found that in many plants, such as rice and barley, nutrient deficiencies caused an increase in secondary metabolites. As plant density increases, competition for resources, such as light and nutrients, increases. Competition among plants increases stress, which can increase secondary metabolites such as glucosinolates (Phong et al. 2019). In addition, Koralewska et al. (2007) found that sulfur deprivation increased sulfur uptake 4-fold compared with sulfate-rich environments, suggesting that a lack of sulfur and sulfates resulting from competition could increase sulfur uptake and storage.

Pepper plants increased in potassium at a high density, whereas beans had increased potassium at a low density (Table 5). Many studies do not report on the leaf mineral composition of fruiting crops under various planting densities, thus leaving a dearth of information. Rajaraman and Pugalendhi (2013) reported that okra (*Abelmoschus esculentus* L. var. Moench) leaves had a greater potassium content at lower planting densities. Conversely, Matsoukis et al. (2015) found that shading increased potassium content in West Indian lantana (*Lantana camara* L.). Menzel and Simpson (1988) found that shading did not affect the foliar potassium content in passionfruit (*Passiflora edulis* f. *edulis* × *P. edulis* f. *flavicarpa* hybrid, E-23), whereas iron, calcium, and magnesium increased, and phosphorus declined.

Planting density effect on pepper fruit length. At the greater planting density (8 plants/m^2), pepper plants produced longer fruit compared with the low planting density (4 plants/m^2) (Table 6). These findings are unusual compared with past research. Kim et al. (1999) and Daşgan and Abak (2003) found no significant difference in pepper size at increased planting densities, whereas Islam et al. (2018) found that pepper fruit length decreased as plants were spaced more closely. Nasto et al. (2009) found that peppers planted at densities of 4.8 plants/m^2 and less had a greater fresh weight and diameter compared with higher densities. Aminifard et al. (2012) concurred, finding that closer spacing produced less and smaller fruit than wider spacing. However, plots spaced at 20 × 50 cm and supplemented with nitrogen fertilizer at 100 kg·ha^{-1} did not produce fruit significantly different from plots spaced at 20 × 100 and 30 × 100 cm supplemented with less nitrogen, suggesting that addition of nitrogen has the potential to override the reducing effects of crowding (Aminifard et al. 2012). In addition, the heat of the hoophouse in our experiment may have affected fruit growth and development, as high temperatures can cause flower drop and reduced growth (Pagamas and Nawata 2008; Thuy and Kenji 2015).

Table 6. Physical characteristics and approximate sugar content of banana pepper and pole bean fruit at two planting densities in aquaponic systems set up in a hoophouse in Stillwater, OK, USA.

Plant species and density	Total no. of fruit	Total fresh wt (g)	Avg individual fresh wt (g)	Length (cm)	°Brix
Pepper					
8 plants/m^2	165.0 a[i]	2464.1 a	23.4 a	12.4 a	5.6 a
4 plants/m^2	115.5 a	3872.2 a	21.3 a	11.1 b	5.8 a
P value	0.1898^{NS}	0.1208^{NS}	0.0657^{NS}	<0.0001***	0.5150^{NS}
Bean					
12 plants/m^2	165.0 a	5218.3 a	6.2 a	12.1 a	6.4 a
6 plants/m^2	115.5 a	3894.1 a	5.4 a	12.2 a	6.3 a
P value	0.1898^{NS}	0.1208^{NS}	0.2129^{NS}	0.4443^{NS}	0.5162^{NS}

[i]Means within a column followed by the same lowercase letter are not significantly different by Tukey's comparison in linear mixed models ($P \leq 0.05$).
NS, *** Nonsignificant or significant at $P \leq 0.001$, respectively.

Conclusion

Plants with larger leaves, such as kale, require increased growing space, whereas herbs, such as cilantro, do not. Fruit plants, such as banana peppers and pole beans, may thrive under crowded conditions, especially in aquaponics, as nitrogen is usually in excess. Research on planting density of several different categories of plants in aquaponics has not been done previously with both leafy greens and fruit.

References Cited

Afolabi KA. 2020. Productivity of kale (Brassica oleracea var. acephala) and Nile tilapia (Oreochromis niloticus) culture in aquaponic systems (master's thesis), The American University, Cairo, Egypt.

Aghajanzadehdivaei T. 2015. Sulfur metabolism, glucosinolates and fungal resistance in *Brassica* (master's thesis). University of Groningen, Groningen, Netherlands.

Ahmad F, Mehta D, Verma R. 2021. Effect of mulching and planting density on production of sweet banana pepper (*Capsicum annuum* L.). Int J Chem Stud. 9(1):1373–1378. https://doi.org/10.22271/chemi.2021.v9.i1t.11413.

Akinwole AO, Adeola IO. 2012. Interrelationship of temperature, pH, dissolved oxygen and nitrogenous wastes in fish culture systems. Niger J Rural Ext Devel. 6(1):38–42.

AlShrouf A. 2017. Hydroponics, aeroponic and aquaponic as compared with conventional farming. Am Sci Res J Eng Technol Sci. 27(1): 247–255.

Aminifard MH, Aroiee H, Ameri A, Fatemi H. 2012. Effect of plant density and nitrogen fertilizer on growth, yield and fruit quality of sweet pepper (*Capsicum annum* L.). Afr J Agric Res. 7(6):859–866. https://doi.org/10.5897/AJAR10.505.

Aminifard MH, Aroiee H, Karimpour S, Nemati H. 2010. Growth and yield characteristics of paprika pepper (*Capsicum annum* L.) in response to

plant density. Asian J Plant Sci. 9(5):276–280. https://doi.org/10.3923/ajps.2010.276.280.
Ani JS, Manyala JO, Masese FO, Fitzsimmons K. 2022. Effect of stocking density on growth performance of monosex Nile tilapia (*Oreochromis niloticus*) in the aquaponic system integrated with lettuce (*Lactuca sativa*). Aquac Fish. 7(3):328–335. https://doi.org/10.1016/j.aaf.2021.03.002.
Arjona H. 1980. Effect of plant spacing and nitrogen fertilizer levels on yield, leaf chlorophyll content and nitrate reductase activity of broccoli (*Brassica oleracea* L. var. *italica, Plenck*) (Master's thesis). Kansas State University, Manhattan, KS, USA.
Baßmann B, Harbach H, Weißbach S, Palm HW. 2020. Effect of plant density in coupled aquaponics on the welfare status of African catfish, *Clarias gariepinus*. J World Aquac Soc. 51(1):183–199. https://doi.org/10.1111/jwas.12574.
Bennett E, Gawthrop F, Yao C, Boniface C, Ishihara H, Roberts J, Wagstaff C. 2013. Effects of planting density and nitrogen application on seed yield and other morphological traits of the leafy vegetable kale (*Brassica oleracea*). Aspect Appl Biol. 119:201–216.
Bhatnagar A, Pooja D. 2013. Water quality guidelines for the management of pond fish culture. J Environ Sci. 3(6):1980–2009. https://doi.org/10.6088/ijes.2013030600019
Boxman SE, Nystrom M, Capodice JC, Ergas SJ, Main KL, Trotz MA. 2017. Effect of support medium, hydraulic loading rate and plant density on water quality and growth of halophytes in marine aquaponic systems. Aquac Res. 48(5):2463–2477. https://doi.org/10.1111/are.13083.
Chishaki N, Horiguchi T. 1997. Responses of secondary metabolism in plants to nutrient deficiency. Soil Sci Plant Nutr. 43(Suppl 1):987–991. https://doi.org/10.1080/00380768.1997.11863704.
Clark M, Tilman D. 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett. 12(6):064016. https://doi.org/10.1088/1748-9326/aa6cd5.
Daşgan H, Abak K. 2003. Effects of plant density and number of shoots on yield and fruit characteristics of peppers grown in glasshouses. Turkish J Agric For. 27(1):29–35.
El-Essawy H, Nasr P, Sewilam H. 2019. Aquaponics: A sustainable alternative to conventional agriculture in Egypt—A pilot scale investigation. Environ Sci Pollut Res Int. 26(16):15872–15883. https://doi.org/10.1007/s11356-019-04970-0.
Islam MD, Miah MY, Kamal MZU, Farhana N. 2018. Effects of micronutrient and spacing on growth and chlorophyll content of rice. Int J Environ Agric Biotechnol. 3(5):1765–1771.
John J, Mahalingam PR. 2021. Automated fish feed detection in IOT based aquaponics system, p 286–290. In: 2021 8th International Conference on Smart Computing and Communications. Kochi, Kerala, India. IEEC. https://doi.org/10.1109/ICSCC51209.2021.9528186.
Jones S. 2002. Evolution of aquaponics. https://aquaponics.com/wp-content/uploads/articles/evoluton-of-Aquaponics.pdf. [accessed 17 Jul 2025].
Kahn BA, Maness NO. 2010. Row arrangements, seeding rates, and gibberellic acid treatments to improve yield of machine-harvested cilantro. HortScience. 45(7):1049–1051. https://doi.org/10.21273/HORTSCI.45.7.1049.
Kim HS, Pae DH, Choi DJ, Jang KS, Cho JL, Kim T. 1999. Growth, yield and quality of tunnel-cultured red pepper (*Capsicum annuum* L.) as affected by plant spatial arrangement. Korean Soc Hortic Sci J. 40:657–661.
Koralewska A, Posthumus FS, Stuiver CEE, Buchner P, Hawkesford MJ, De Kok LJ. 2007. The characteristic high sulfate content in *Brassica oleracea* is controlled by the expression and activity of sulfate transporters. Plant Biol (Stuttg). 9(5):654–661. https://doi.org/10.1055/s-2007-965438.
Li J, Martin A, Carver L, Armstrong S, Givens S, Walters K. 2024. Optimizing sowing density for parsley, cilantro, and sage in controlled environment production: Balancing productivity and plant quality. HortTechnology. 34(3):305–312. https://doi.org/10.21273/HORTTECH05381-23.
Love DC, Fry JP, Li X, Hill ES, Genello L, Semmens K, Thompson RE. 2015. Commercial aquaponics production and profitability: Findings from an international survey. Aquaculture. 435:67–74. https://doi.org/10.1016/j.aquaculture.2014.09.023.
Mangan F, Kozower C, Barker A, Bramlage W, Costello H, Anderson M, Baranek J, Sullivan-Werner L, Anziani D, Caminero F, Johnson K, Pearson M, Webber D. 2001. Effects of organic soil amendments, seeding density, cultivar selection, and postharvest practices on cilantro (*Coriandrum sativum* L.) yield quality, p 6–10. In: Proceedings of the 45th annual meeting.
Matsoukis A, Gasparatos D, ChronopoulouSereli A. 2015. Mepiquat chloride and shading effects on specific leaf area and K, P, Ca, Fe and Mn content of *Lantana camara* L. Emir J Food Agric. 27(1):121. https://doi.org/10.9755/ejfa.v27i1.17450.
Menzel CM, Simpson DR. 1988. Effect of continuous shading on growth, flowering and nutrient uptake of passionfruit. Sci. Hortic. 35(1–2):77–88. https://doi.org/10.1016/0304-4238(88)90039-8.
Mohammadi S, Amirian S, Hosseini S. 2021. An analysis of the consequences of urban creep in the development of surrounding rural settlements: Case Study: Villages around the city of Marivan. Geogr Territor Spatial Arrang. 11(38):1–38. https://doi.org/10.22111/gaij.2021.6030.
Mondal M, Puteh A, Ismail MR, Rafii MY. 2013. Optimizing plant spacing for modern rice varieties. Int J Agric Biol. 15(1):175–178.
Naiki IA, Gupta AJ. 2010. Effect of plant density and integrated nutrient management on growth, yield, quality and economics of kale (*Brassica oleracea* var. acephala) in temperate region. Indian J Agric Sci. 80(1):80–84.
Nasiri A, Samdaliri M, Shirani Rad A, Shahsavari N, Mosavi KA, Jabbari H. 2017. Effect of plant density on yield and physiological characteristics of six canola cultivars. J Sci Agric. 1:249–253. https://doi.org/10.25081/jsa.2017.v1.819.
Nasto TH, Balliu A, Zeka N. 2009. The influence of planting density on growth characteristics and fruit yield of peppers (*Capsicum annuum* L.). Acta Hortic. 830:609–912. https://doi.org/10.17660/ActaHortic.2009.830.88.
Noboa CS, Lima BMD, Bettan SR, Gupta D, Bernardi MRV, Purquerio LFV, Sala FC. 2022. Hydroponic kale: Effects of row spacing and number of plants per cell on yield and quality. Aust J Crop Sci. 16(5):596–604. https://doi.org/10.21475/ajcs.22.16.05.p3561.
Okomoda VT, Oladimeji SA, Solomon SG, Olufeagba SO, Ogah SI, Ikhwanuddin M. 2023. Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. Food Sci Nutr. 11(3):1157–1165. https://doi.org/10.1002/fsn3.3154.
Pagamas P, Nawata E. 2008. Sensitive stages of fruit and seed development of chili pepper (*Capsicum annuum* L. var. Shishito) exposed to high-temperature stress. Sci Hortic. 117(1):21–25. https://doi.org/10.1016/j.scienta.2008.03.017.
Painkara SK, Chandrakar DK, Langangmeilu G, Paraye PM, Verma AK, Patel A. 2024. Growth analysis of coriander (*Coriandrum sativum* L.) as influenced by different sowing dates and planting geometry in Chhattisgarh Plains zone. IJECC. 14(3):797–803. https://doi.org/10.9734/ijecc/2024/v14i34088.
Pandey B, Seto KC. 2015. Urbanization and agricultural land loss in India: Comparing satellite estimates with census data. J Environ Manag. 148:53–66. https://doi.org/10.1016/j.jenvman.2014.05.014.
Parsipour HG, Popovic S, Behzadfar M, Skataric G, Spalevic V. 2019. Cities expansion and land use changes of agricultural and garden lands in peri-urban villages: (Case study: Bojnurd). Agric For. 65(3):173–187. https://doi.org/10.17707/AgricultForest.65.3.14.
Patil BN, Ingle VG, Patil SS. 2003. Effect of spacings and nitrogen levels on growth and yield of knol-khol (*Brassica oleracea* var. caulorapa) cv. White Vienna. Annals Plant Physiol. 17(2):110–113.
Phong LV, Choi J, Kim S, Park J, Ricardo H. 2019. Optimizing plant spacing and harvest time for yield and glucosinolate accumulation in watercress (*Nasturtium officinale* L.) grown in a hydroponic system. Hortic Sci Technol. 37(6):733–743. https://doi.org/10.7235/HORT.20190073.
Pickens J, Danaher J, Wells D. 2016. Greenhouse crops and cropping systems for commercial aquaponics. Pub no. 5009. Southern Regional Agriculture Center, Lexington, KY, USA.
Prăvălie R, Patriche C, Borrelli P, Panagos P, Roșca B, Dumitraşcu M, Nita I-A, Săvulescu I, Birsan M-V, Bandoc G. 2021. Arable lands under the pressure of multiple land degradation processes: A global perspective. Environ Res. 194:110697. https://doi.org/10.1016/j.envres.2020.110697.
Rajaraman G, Pugalendhi L. 2013. Potential impact of spacing and fertilizer levels on the flowering, productivity and economic viability of hybrid Bhendi (*Abelmoschus esculentus* L. Moench) under drip fertigation system. Am J Plant Sci. 4(9):1784–1789. https://doi.org/10.4236/ajps.2013.49219.
Sharma A, Naruka IS, Shaktawat RP, S. 2016. Effect of row spacing and nitrogen on growth and yield of coriander (*Coriandrum sativum* L). J Krish Vigy. 5(1):49. https://doi.org/10.5958/2349-4433.2016.00032.5.
Shi K, Chen Y, Yu B, Xu T, Li L, Huang C, Liu R, Chen Z, Wu J. 2016. Urban expansion and agricultural land loss in China: A multiscale perspective. Sustainability. 8(8):790. https://doi.org/10.3390/su8080790.
Singh B, Yadav PK, Maurya RP, Singh P. 2003. Effect of spacing and GA_3 on yield of knol-khol (*Brassica oleracea* var. gongylodes L.). Haryana J Hortic Sci. 32(3/4):293–294. https://www.cabidigitallibrary.org/doi/full/10.5555/20043121656.
Somerville C, Cohen M, Pantanella E, Stankus A, Lovatelli A. 2014. Small-scale aquaponic food production: Integrated fish and plant farming. Food and Agriculture Organization, Rome, Italy.

Stone N, Shelton JL, Haggard BE, Thomforde HK. 2013. Interpretation of water analysis reports for fish culture. Pub. No. 4606. Southern Regional Aquacultural Center, College Station, TX, USA.
Surnar SR, Surnar OP, Sharma OP, Saini VP. 2015. Aquaponics: Innovative farming. Int J Fish Aquac Stud. 2(4):261–263.
Thuy TL, Kenji M. 2015. Effect of high temperature on fruit productivity and seed-set of sweet pepper (*Capsicum annuum* L.) in the field condition. J Agric Sci Technol. 5(2015): 515–520. https://doi.org/10.17265/2161-6256/2015.12.010.
World Bank. 2022. Food security: Rising food insecurity. https://www.worldbank.org/en/topic/agriculture/brief/food-security-update. [accessed 24 Jun 2024].
World Food Programme. 2023. A global food crisis. https://www.wfp.org/global-hunger-crisis. [accessed 24 Jun 2024].
Xiao S, Chen S-Y, Zhao L-Q, Wang G. 2006. Density effects on plant height growth and inequality in sunflower populations. J Integr Plant Biol. 48(5):513–519. https://doi.org/10.1111/j.1744-7909.2006.00265.x.
Zaniboni A, Tassinari P, Torreggiani D. 2024. GIS-based land suitability analysis for the optimal location of integrated multi-trophic aquaponic systems. Sci Total Environ. 913:169790. https://doi.org/10.1016/j.scitotenv.2023.169790.