Optimizing Carrot Growth in Static Hydroponic Systems

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Abstract: The experimental investigation evaluates static hydroponics systems to sustainably produce carrots and alleviate food insecurity via alternative modes of small-scale agriculture. The research compares different carrot cultivars in a variety of substrates to determine which combinations yielded the most produce (fresh weight) and aesthetic product (length). The focus was on four carrot cultivars: 'Danvers', 'Yaya Hybrid', 'Chantenay', and 'Imperator'. These cultivars were selected due to their commercial popularity, sugar content, soil type durability, and observed yield potential from previous research done by the Michaels lab.[11,12] Substrates included a mix of nonrenewable and renewable materials including perlite, coconut coir, coarse sand, and vermiculite. Hydroponics is commercially used for leafy greens; however, this study aims to expand its applications to root vegetables like carrots to diversify dietary nutrients for consumers and provide growers with more options. Results from this study indicated that sand-dominated substrates, especially 75% sand medium, yielded on average the longest taproot length and fresh weight. Yaya produced the longest carrot. However, Chantenay, while much stouter in appearance, yielded similar fresh weights. Overall, sand-dominated substrates outperformed mediums with perlite.

Introduction

Hydroponics is a method of soil-less plant cultivation.[1] This method of cultivation suspends plant roots in nutrient solutions needed for growth. Static hydroponics is a subset of hydroponics which similarly employs a nutrient solution as the main body of plant sustenance but requires no aeration or pumps to circulate water.[2] The solution is stagnant and replenished periodically, with an air gap between the solution surface and plant roots to allow for gas exchange (necessary oxygen uptake for plant respiration).[3] Plants grown in soil can obtain oxygen through pockets of air in the ground. However, because hydroponics are saturated environments, nutrient levels are either filled only partway to the top of containers to leave space between the nutrient surface and container lid or contain a semipermeable barrier to moderate moisture uptake.

Hydroponic systems are currently being considered to address mounting concerns regarding sustainable agriculture, limited land in urban areas, and food deserts.[4] With the effects of climate change and increasingly fragile supply chains, seeking alternative routes to resilient food systems is of utmost importance, especially as the global population continues to grow, with urban populace projected to reach ten billion by mid-century.[5,6]

Historically, hydroponics has been better suited for leafy greens such as lettuce, spinach, and herbs due to their shallow root system and the confined space associated with hydroponics.[7] Lettuce does not require as much aeration in comparison with other greens and is therefore a great candidate for static hydroponics. Building upon a static hydroponic system designed by the University of Hawaii featuring lettuce grown in shallow trays, Professor Tom Michaels from the University of Minnesota adapted this design to deeper compact plastic totes usually used for recreational storage.[8] The resulting "hydroponic salad table" (HST) has successfully produced leafy green varieties and new experiments are exploring production of root vegetables, specifically carrots (*Daucus carota* L.).[3] Carrots have the highest carotenoid content among foods and are consumed globally. Carotenoids are associated with protective effects against cancer and other chronic diseases, leading to increased market demand as preventative health dominates public conversations.[9, 10] Carrots' universal consumption and high dietary benefits makes them ideal candidates for small scale experimentation that is applicable to a large demographic.

This research further expands upon carrot compatibility with the HST design by optimizing taproot growth (length from crown to tip) and yield (fresh weight, right after harvest). Another optimized carrot characteristic is "hairiness," or secondary root growth. When in moist environments, carrots are prone to branch out from the main taproot, resulting in lateral roots that can detract from aesthetics and main taproot yield. To investigate carrots in the HST system, multiple cultivars were grown in varying soil compositions consisting of perlite, coconut coir, coarse sand, and vermiculite in a greenhouse environment. The focus was on four carrot cultivars: 'Danvers', 'Yaya Hybrid', 'Chantenay', and 'Imperator'. These cultivars were selected due to their commercial popularity, sugar content, soil type durability, and observed yield potential from Michaels's previous HST research.[11,12] In 2018, previous trials done by Michaels and Trinh compared two substrate mixes: 50% perlite/25% coconut coir/25% vermiculite vs 75% perlite/25% sand. The 50% perlite mix yielded greater taproot growth with extensive secondary root growth, whereas the 75% perlite mix yielded less taproot growth with less secondary root growth.[16]

Referencing the 2018 trials, this study further investigates whether perlite is responsible for diminished taproot growth (length) and if sand promotes less secondary root growth (yield). The hypothesis predicts that carrot yield will increase with sandy substrates without the presence of perlite. Medium variables were supplemented by coconut coir and/or vermiculite. Coconut coir and vermiculite were chosen due to their renewable nature. Examining several substrates composed of renewable resources has implications for replenishing soil health and cultivation potential across geographic borders.

Independent variables include substrates containing three different ratios of perlite/coconut coir/sand and two ratios of sand/coconut coir/vermiculite to identify which substrate promotes greater taproot growth and yield while diminishing secondary root growth. Integration of hydroponically grown carrots into consumer diets is desired in efforts to simultaneously meet sustainable food system demands both urban and worldwide. Carrots are nutrient dense, improving diet quality while being a palatable vehicle to empower individuals and communities to begin small-scale agriculture. Static hydroponics, specifically the HST model, is preferred for this endeavor as it is a compact system (2x2 ft.). Other advantages are minimal energy input, accessibility in terms of construction and cost, low maintenance oversight, and suitability to land and water constrained areas.

Materials & Methods

One hundred seeds for each carrot cultivar ('Danvers', 'Yaya Hybrid', 'Chantenay', and 'Imperator') were used, totaling four hundred seeds. For the static hydroponic system, five ten-gallon plastic totes with lids were required, with one extra tote as a mixing container. Five two-inch diameter PVC pipes were trimmed to approximately sixteen inches in length to be used as a channel for watering the system. Lids were modified to include holes to hold net pots and PVC pipe, and edges trimmed to fit within the tote. Forty two-inch net pots were used as inserts for the false floor wicking mechanism. String or similar substitutes such as twist ties were used to visually divide each tote into quadrants along with twenty plant markers (four different colors, five markers for each color) to demarcate cultivars in respective quadrants and totes.

For the substrates, the following media were used in various combinations: perlite, sand, vermiculite, and coconut coir. Throughout the entire experiment, spanning two repetitions (rep) or trials of growth for five totes, 560 grams of hydroponic 16-4-17 nutrient powder was used.

All carrots were grown in the HST model under greenhouse conditions, with Rep 1 seed germination starting the end of September 2019. Greenhouse conditions were kept at long days of sixteen hours of natural and artificial light simulation (high pressure sodium lamps), at 21°C.[13] Carrots took twelve weeks to mature, with Rep 1 harvest at the end of December 2019.[14] To ensure sufficient data and precision, a second trial was replicated at the end of December 2019 for another growth cycle, which terminated at the end of March 2020.

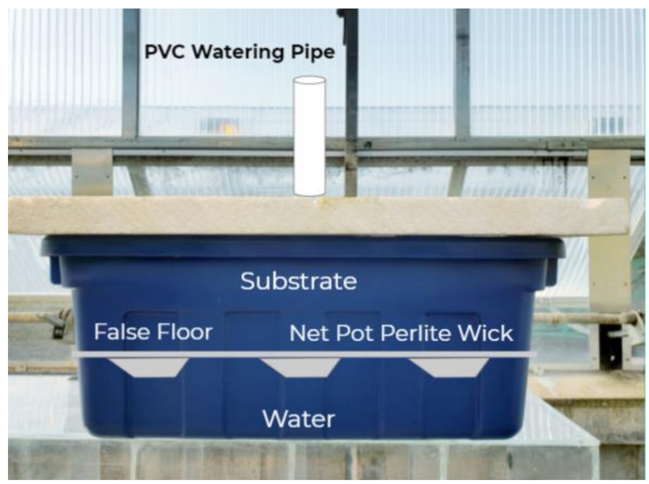

Figure 1. HST System with components labeled

There were five HST set-ups, one for each substrate treatment:

- 10% perlite | 45% coir | 45% sand
- 25% perlite | 37.5% coir | 37.5% sand
- 50% perlite | 25% coir |25% sand

- 50% sand | 25% coir | 25% vermiculite
- 75% sand | 12.5% coir | 12.5% vermiculite

All four cultivars were grown in each HST at the same time, ten plants per cultivar. Each cultivar was grown in one of the quadrants in the tote, with clear demarcation via plant markers.

The HST model infrastructure was slightly modified to accommodate for carrot growth, as it is a root vegetable with extensive root systems unlike the shallow root set-up previously used for leafy greens. Thus, a false floor was employed to provide greater depths of substrate to support carrot roots.[15] The original HST model for leafy greens also utilized a wick system in which roots, situated in a thin lid slightly above the water, wicked up nutrients from the solution via the substrate. For root vegetable HST, a false floor placed inside the tote created a separation between the nutrient reservoir and deeper substrate section. Holes drilled into the lid and plugged with perlite-filled net pots acted as a false floor to provide a wicking mechanism between the nutrient reservoir and the substrate.

HST totes were filled weekly via the PVC pipe directly connected to the water, maintaining a constant ~2.5 gallon nutrient reservoir. Each tote received 28 grams of 16-4-17 hydroponic nutrient powder in Week 4 and Week 8 (28 grams per 2.5 gallon/9.5 liters of water = 471 ppm N). Nutrient application was abstained for the first four weeks of growth and only applied twice to provide nutrient boost at critical stages of growth (Week 4, taproot lengthening period) and maturation (Week 8, taproot filling period). There was no other interference except for the final harvest at Week 12.

Preparing the HST with a False Floor

A hole 0.5 inches in diameter was drilled into the handle side of five totes, one quarter of the way up from the bottom of the tote to allow excess water to escape, preventing oversaturation of the substrate.

Nine holes were created in a 3x3 array in five of the lids, ensuring large enough diameters to hold the net pot (approximately two inches in diameter). The lid edges were trimmed so that the lid fit squarely within the tote, flushed against the sides. One tote and accompanying lid were left unmodified to be the substrate mixing container.

Net pots were inserted into eight of the holes, leaving the center hole of the 3x3 array empty. The lip of the net pots rested atop the lid holes. Tape was used on the underside of the lid to secure some of the net pots. The perforated lid was slid down from the top of the tote to be level with the excess water hole. Each net pot was filled with rinsed perlite to act as a wicking semipermeable barrier between the substrates and nutrient solution (Figure 1).

The PVC pipe was inserted into the center hole of the 3x3 array. This was the watering pipe where nutrient powder and water entered. Once the substrates were added, the pipe was supported to stand upright.

Preparing the Substrate

The unmodified tote was used to mix the substrates. Halfway up from the bottom of the tote is an indent. This indent was taken as the “100% line” for measuring the proportion of each substrate component. For example, for the 50% sand/25% coir/25% vermiculite mix, sand was added into the tote via a hand scoop until halfway to the indent. For the 25% coir and 25% vermiculite, each component was added to occupy half of the remaining space up to the indent line by visual approximation. Once all components were added, the substrate was mixed by hand for three minutes to form a heterogeneous mixture. Once a substrate was mixed, it was transferred to a tote. This method was done for all substrates with respective proportions adjusted using the approximation system.

Planting the Seeds

After demarcating quadrants in the filled totes, ten seeds of each cultivar were planted in their respective quadrants in a 2x5 array. Seeds were planted one inch below the substrate surface.

Maintenance & Harvest

Each tote was watered weekly via the PVC pipe until water leaked out of the excess water hole. During Week 4 and Week 8, 28 grams of hydroponic 16-4-17 nutrient powder was applied to each tote. The powder was funneled into the pipe and washed down with water.

In Week 12, all units were harvested. Carrot tops were discarded and composted. The length (cm), width (cm), and fresh weight (g) were measured for each unit. Length was measured from the crown to the tip of taproot growth. Width was measured at the widest part of the root. Fresh weight was taken immediately after harvest. All measurements were rounded to the nearest integer or one decimal place when possible.

Results & Discussion

Results Description

Analysis was conducted using Excel and statistical software JMP. Initial comparisons were done for individual cultivars between mediums. Fresh weight and length averages per cultivar are shown below (Figure 2, 4).

Aggregate data for all cultivars/medium combinations regarding fresh weight and length was compiled as well (Figure 3, 5). For width average comparisons see Appendix A, B, C. A total of 228 unique units were harvested and measured during the study. As stated before, 400 seeds were planted over two trials. Results illustrated varying mortality rates between cultivars.

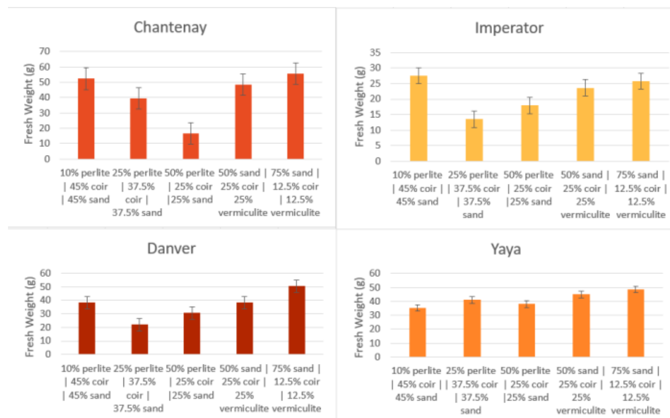

Figure 2. Fresh weight averages between different substrates per cultivar

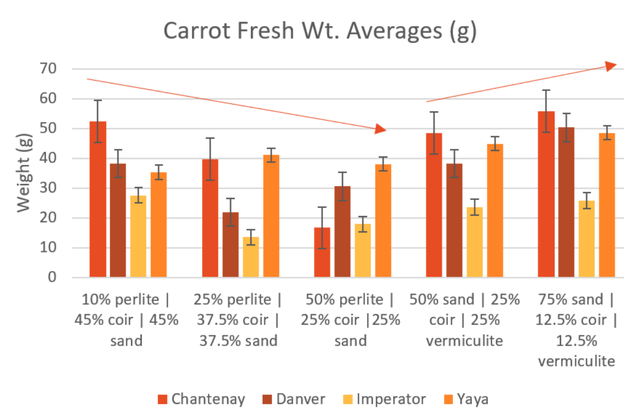

Figure 3. Fresh weight averages for all four cultivars per substrate

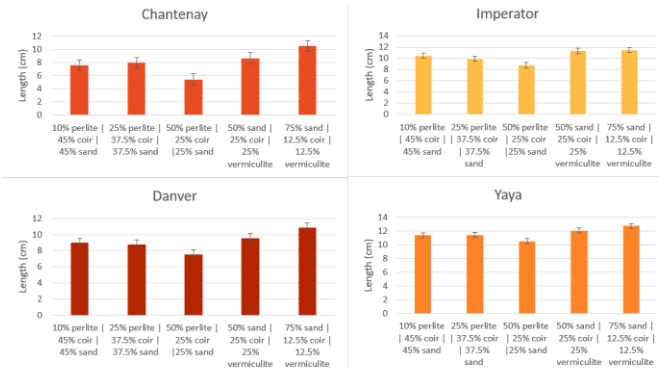

Figure 4. Length averages between substrates per cultivar

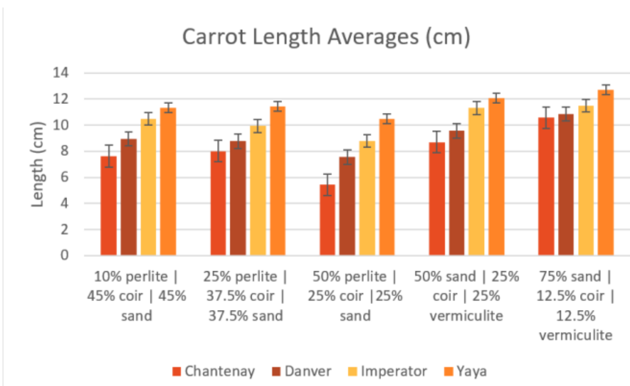

Figure 5. Carrot length averages for all four cultivars per substrate

Across all cultivars except Yaya, the 10% perlite mix fared best of substrates containing perlite, with fresh weight (yield) progressively decreasing with increasing proportions of perlite. Yield differences between the 10% and 50% perlite mix ranged from 8-36 grams. Between the sand dominated substrates, increasing proportions of sand produced greater yields with the 75% sand mix performing best. Yield gains ranged from 2-12 grams when comparing 50% to the 75% sand. Both these trends are consistent with the hypothesis that sandier substrates and the absence of perlite will promote higher yields.

Secondary root growth or hairiness was noted qualitatively on a scale of 1-3, with 1 being hairy, 2 somewhat hairy, and 3 being not hairy. However, data was not collected for every cultivar in every substrate due to time constraints and greenhouse closures from the COVID-19 pandemic. Additionally, due to two trials and harvest times, it was difficult to judge what constituted hairy relative to each cultivar and units between trials. Photographic data was equally hard to measure as pictures captured only one side of the carrot when secondary roots are present radially around the entire taproot. Therefore, secondary root growth data was discarded as inconclusive. However, based on the limited data observed, perlite substrates generally yielded hairy carrots with sparse clumps of long and thin secondary roots. Carrots grown in sand substrates ranged from less to very hairy and exhibited clumping of secondary roots.

Factorial Analysis

In-depth evaluation for significant differences was conducted using a factorial analysis through JMP. Of particular note is identification of significant variance from the factors (substrate, cultivar, repetition) on the dependent variables (weight, length, width).

A cursory examination of the actual by predicted plots provided insight into how much influence the factors (substrate, cultivar, rep) had on the variation in data. If there had been perfect alignment between actual and predicted, all data points would lay on the bright red line. The extent to which the data diverges from the line illustrates how much unexplained variation there is in the model. In the case of Length for example, the R-Square (RSq) is 0.41, meaning 41% of the variance can be attributed to the factors. For width it was 54% and fresh weight 47%. These numbers can be deemed significant. However, further analysis was taken from the Effects Test Table (Table 1).

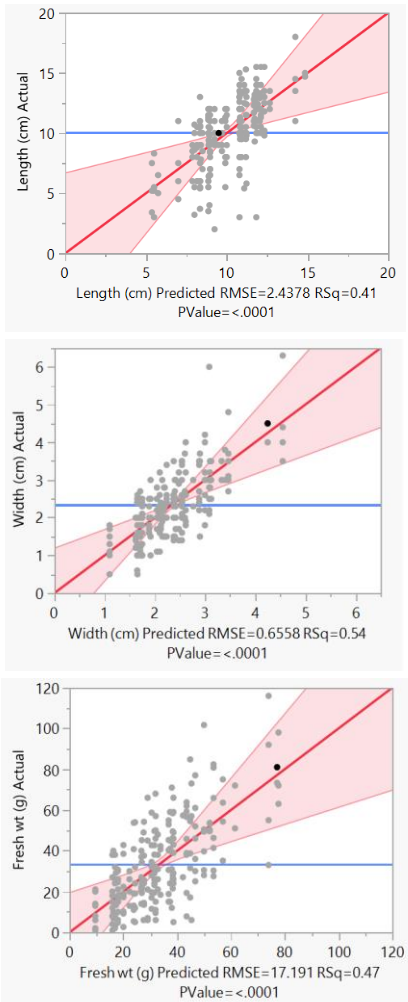

Figure 6. Actual by Predicted plots for length, width, fresh weight (L-R) for all cultivars and medium substrates

Length Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Medium	4	4	279.04349	11.7385	<.0001*
Variety	3	3	320.66639	17.9859	<.0001*
Medium*Variety	12	12	31.20977	0.4376	0.9466
Rep	1	1	18.32283	3.0831	0.0807
Medium*Rep	4	4	60.26505	2.5352	0.0416*
Variety*Rep	3	3	7.61018	0.4268	0.7340
Medium*Variety*Rep	12	12	116.43470	1.6327	0.0855

Table 1. Effects Tests table for length as data interpretation example. Medium = substrates. Variety = carrot cultivar. Rep = Trial in which carrots were grown (Trial 1 in fall or Trail 2 in spring).

The Prob >F column provided the probability that the F Ratio indicated could be that large or larger by chance. This means the probability that the analysis indicates a significant effect from Medium, when in fact there is no real effect, is very low (<0.0001%), leading to a great deal of confidence that there is an effect of Medium. Values in orange are considered highly significant, values in red are significant.

Length and fresh weight data will be closely examined in the discussion hence forth as the primary carrot characteristics to optimize in this study (Figure 3, 5). Factors that influenced carrot length the most were medium, variety, and medium*rep (Prob > F: <.0001, <.0001, .0416 respectively). Factors with greatest influence on fresh weight were medium, variety, and medium*rep with Prob > F: <.0001 for all (Table 2).

	Length	Fresh Wt	Width
Medium	<.0001*	<.0001*	0.0745
Variety	<.0001*	<.0001*	<.0001*
Medium*Variety	0.9466	0.0634	0.0065*
Rep	0.0807	0.1925	0.0009*
Medium*Rep	0.0416*	<.0001*	<.0001*
Variety*Rep	0.734	0.475	0.0119*
Medium*Variety*Rep	0.0855	0.0022*	0.1359

Table 2. Effects Tests summary table for length, fresh weight, and width

Factorial Analysis - Length

For taproot length, the factors medium, variety, and medium*rep had the largest effect (Table 2). To examine this significance, least squares mean tables were produced to observe the “interaction” or effect of factor on dependent variables.

For mediums’ effect on taproot length, a significant decrease of more than 1 cm was observed for the 50% perlite medium compared to other perlite mediums: 9.629 vs 8.069 cm (Appendix D). Similarly for sand dominated mediums, a significant increase of more than 1 cm was observed for the medium with more sand: 10.473 vs 11.769 cm. This is congruent with the hypothesis.

An increase in taproot length was dependent on the variety, with Yaya (4) yielding the longest carrot by approximately 1-3 cm, on average at 11.77 cm. Chantenay (1) produced the shortest at 8.04 cm on average (Appendix E).

Important to note is the interaction between medium and rep. This interaction indicates that length was influenced by the rep depending which medium the carrots were grown in, whether it was Trial 1 or Trial 2 (Figure 7). This interaction was observed in the 10% perlite medium but to a less significant degree than the 75% sand medium (Appendix F). The data implied that carrots grown in the 75% substrate were on average ~3 cm longer than the ones grown in the first trial.

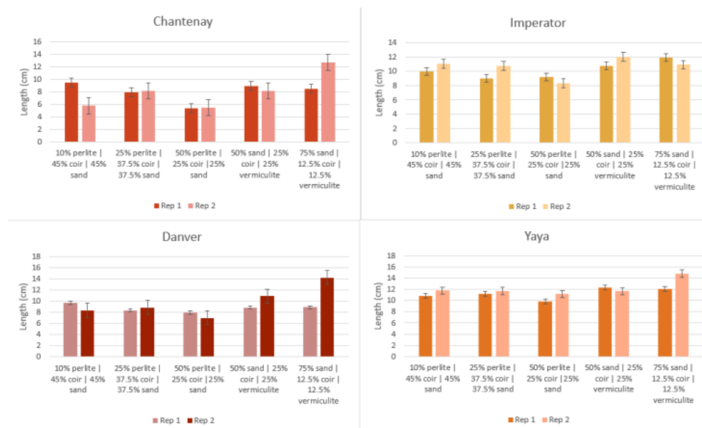

Figure 7. Carrot length averages between Rep 1 and Rep 2

The length differences between reps could be attributed to time of growth and changing light conditions. Rep 1 was grown in the fall (Sep-Dec 2019) whereas Rep 2 was grown in the winter/spring (Jan-Mar 2020). While light and temperature parameters were kept constant, the type of light changed. Rep 1 had diminishing natural light quantities as the winter progressed, whereas Rep 2 had increasing natural light intake as spring approached. Thus, Rep 2 had higher quality light and photon intake, potentially leading to greater length.

Factorial Analysis - Fresh Weight

For fresh weight, similarly the factors medium, variety, and medium*rep had the largest influence (Table 2).

For mediums' effect on carrot fresh weight, a significant decrease of more than 12 grams was observed for the 50% perlite medium compared to other perlite mediums (Appendix G). For sand dominated mediums, a significant increase of nearly 10 grams was observed for 75% sand compared to other sand substrates (Figure 3). Medium's effect on fresh weight is consistent with the hypothesis.

Variety also played a significant role in fresh weight, with Chantenay (1) and Yaya (4) yielding approximately the same weight despite having very different lengths in other interactions (Appendix H). Although Chantenay phenotypically is a shorter and stouter carrot, it is wide thus lending weight, whereas Yaya exhibits more taproot growth and is longer. Danver, as a short and thicker carrot, unsurprisingly yielded a heavier carrot at 38.59 grams, not far behind Chantenay and Yaya. Imperator had low yields at 21.60 grams on average, contrary to expectations of a phenotypically longer carrot.

Of the five mediums, three had lower fresh weight averages on Rep 2 (Appendix I). The exceptions are for the 50% perlite and 75% sand mediums, where Rep 2 yielded greater fresh weight averages. The 75% sand substrate yielded significantly higher fresh weight averages upwards of 20 grams compared to all other mediums (Figure 8). Similar to taproot growth and length, which were affected by medium*rep factors, fresh weight may also be dependent on light quality and time of growth. A surprising observation is majority of Rep 2 yields were lower. This runs counter to expectations that crops grown in the spring would produce higher yields, attributed to increasing natural light intake near crop maturation and root filling periods. Despite this reasoning, it is contradicting that the majority of Rep 2 yields were lower.

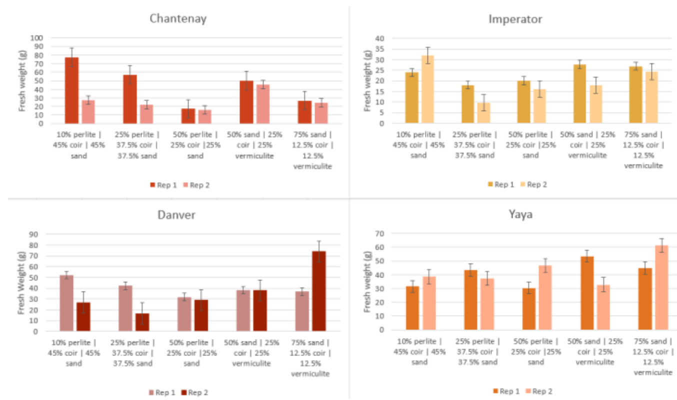

Figure 8. Carrot fresh weight averages between Rep 1 and Rep 2

Tukey Honest Significant Difference (HSD) Analysis

Further analysis was done on the major effect factors for length and fresh weight (medium, variety, medium*rep) to determine whether the influence is statistically significant. The Tukey HSD analysis is a post hoc method that compares the mean difference of data sets. To interpret the data, variables or rows sharing the same letter in any order are not considered significantly different. Those with different letters are considered significantly different. For data related to the variety: Chantenay = 1, Danver = 2, Imperator = 3, Yaya = 4.

Tukey HSD - Length

In the factorial analysis for medium's effect on length, the 50% perlite and 75% sand substrates had differences of greater than 1 cm compared to their respective dominated mediums. The Tukey test confirms that the difference between 50% and 10% perlite is statistically different (B vs C), and that 75% sand performed better than 50% perlite (A vs C), however no other interaction was considered significantly different (Table 9). The main conclusion drawn from this data is that sand dominated substrates perform better than perlite substrates by upwards of 1-3 cm, with relatively little difference in yield within the perlite substrates.

Length: Medium main effect

LSMeans Differences Tukey HSD

α= 0.050 Q= 2.75444

Level				Least Sq Mean
75% sand	A			11.768899
50% sand	A	B		10.473036
10% perlite		B		9.629028
25% perlite		B	C	9.500868
50% perlite			C	8.069221

Levels not connected by same letter are significantly different.

Table 9. Tukey HSD for length based on medium effect

According to the factorial analysis for variety's effect on length, Yaya produced the longest carrot by at least 1 cm and upwards of 3 cm compared to other varieties. The Tukey test confirms that Yaya was significantly longer from the other varieties (A vs B vs C) (Table 10). Significant difference in length due to variety cannot be drawn between Danver (2) and Imperator (3), nor between Danver and Chantenay (1).

Length: Variety main effect

LSMeans Differences Tukey HSD

α= 0.050 Q= 2.59217

Level				Least Sq Mean
4	A			11.767885
3		B		10.410016
2		B	C	9.330774
1			C	8.044167

Levels not connected by same letter are significantly different.

Table 10. Tukey HSD for length based on variety effect

In the factorial analysis for the medium*rep interaction's effect on length, the 75% sand and 10% perlite substrates displayed significant differences between Rep 1 and Rep 2. However, the Tukey analysis indicated significant differences between reps only for the 75% sand and between 75% sand Rep 2 versus 50% perlite Rep 2 (Table 11). This selective difference is interesting to note, as that implies no significant difference between most of the substrates between reps, contrary to the light quality theory presented earlier to explain length differences between reps seen in the factorial analysis.

*Length: Medium * Rep interaction*

LSMeans Differences Tukey HSD

α= 0.050 Q= 3.20213

Level				Least Sq Mean
75% sand,2	A			13.170833
50% sand,2	A	B		10.705000
75% sand,1		B		10.366964
50% sand,1		B	C	10.241071
10% perlite,1		B	C	10.005556
25% perlite,2		B	C	9.883681
10% perlite,2		B	C	9.252500
25% perlite,1		B	C	9.118056
50% perlite,1		B	C	8.130903
50% perlite,2			C	8.007540

Levels not connected by same letter are significantly different.

Table 11. Tukey HSD for length based on medium*rep effect

Tukey HSD - Fresh Weight

In the factorial analysis for medium's effect on fresh weight that upwards of ten gram differences were found between 50% perlite compared to other perlite substrates. Similar differences were found for sand substrates. The Tukey analysis indicated the only significant difference between the perlite substrates was between the 10% and 50% perlite, with 10% advancing towards the top in terms of fresh weight yield compared to all other medium combinations (Table 12). There was no significant difference between the 75% and 50% sand, contrary to initial observations.

Fresh Weight: Medium main effect

LSMeans Differences Tukey HSD

α= 0.050 Q= 2.75444

Level				Least Sq Mean
75% sand	A			47.474554
10% perlite	A	B		38.671528
50% sand	A	B		37.950893
25% perlite		B	C	30.825347
50% perlite			C	25.935813

Levels not connected by same letter are significantly different.

Table 12. Tukey HSD for fresh weight based on medium effect

Unlike variety's effect on length, the effect of variety on fresh weight is less clear. While it was observed that Chantenay produced the most with the greatest fresh weight, Yaya is not significantly different, nor when compared to Danver as indicated by all A's (Table 13). The most significant difference was between all varieties compared to Imperator, which on average yielded nearly 50% less than the highest yielding varieties.

Fresh Weight: Variety main effect

LSMeans Differences Tukey HSD

α= 0.050 Q= 2.59217

Level			Least Sq Mean
1	A		42.411667
4	A		42.081587
2	A		38.590357
3		B	21.602897

Levels not connected by same letter are significantly different.

Table 13. Tukey HSD for fresh weight based on variety effect

In the factorial analysis, most of the substrates (3 out of 5) fared better in Rep 1, once again contrary to the light quality theory. This observation is further supported by the Tukey analysis where every substrate's Rep 1 performed better than in Rep 2, except the 50% perlite and 75% sand (Table 14). However, there is no significant difference between any of the variables except when comparing 75% sand Rep 2 and 25% perlite Rep 2, a combination not priorly discussed in terms of exhibiting significant differences in either analysis.

Fresh Weight: Medium x Rep interaction

LSMeans Differences Tukey HSD

α= 0.050 Q= 3.20213

Level						Least Sq Mean
75% sand,2	A					59.375000
10% perlite,1	A	B				46.151389
50% sand,1	A	B	C			42.368452
25% perlite,1	A	B	C	D		40.147222
75% sand,1		B	C	D	E	35.574107
50% sand,2		B	C	D	E	33.533333
10% perlite,2		B	C	D	E	31.191667
50% perlite,2			C	D	E	26.963294
50% perlite,1				D	E	24.908333
25% perlite,2					E	21.503472

Levels not connected by same letter are significantly different.

Table 14. Tukey HSD for fresh weight based on variety effect

Conclusion

Experimental data supports the hypothesis that sandier substrates with less perlite promoted greater taproot growth (length) and yield (fresh weight). On average across all four cultivars, 10% perlite mix yielded carrots 12 grams heavier than 50% perlite, and the 75% sand mix yielded carrots 10 grams heavier than the 50% sand. For length, the latter mix in both the 10% vs 50% perlite and 50% vs 75% sand produced longer carrots by >1 cm.

Less conclusive is the effect on reducing secondary root growth. For both optimization factors (length and fresh weight), three effects had the greatest influence: medium, variety, and medium*rep. Further analysis confirmed medium and variety as being the most influential factors, while medium*rep remains statistically speculative.

For growers seeking to cultivate carrots in static hydroponic systems such as the HST, based on the study, optimal results can be achieved with the 75% sand/12.5% coconut coir/12.5% vermiculite substrate and Yaya hybrid carrot cultivar. Other grower considerations include time of planting as yield and growth were shown to be potentially affected by light quality (natural vs. artificial).

Future studies can include more trials for statistical accuracy and verification of influences such as the medium*rep interaction. Comparing multiple trials all grown either in the fall versus in the spring can also bring clarity to the light quality theory. Testing other carrot varieties in larger totes will offer insights into bringing this method to scale. Another way to analyze the impact of sand from this study is to view all five substrates as percentage sand. Even though the substrates observed were bifurcated into perlite and sand dominated mediums, another way to interpret the data is to view the perlite substrates as sand substrates as the 10%, 25%, and 50% had sand as a medium component (45%, 37.5%, and 25% respectively).

These insights are important in informing small-scale cultivation, with the goal of building resilient food systems, increasing accessibility to healthy foods, and alleviating food insecurity. Further understanding of carrot/HST dynamics increases the viability of carrots as an option for hydroponic systems, typically reserved for leafy greens. Carrot, a globally consumed, nutrient dense food, is an ideal candidate to initiate discussions regarding alternative agriculture models with lower environmental impacts and shorter supply chains. Furthermore, examining substrates composed of renewable resources (coconut coir, vermiculite, sand) has implications for alleviating soil deterioration and growing applications across geographic borders. This research, built upon prior static hydroponic models, aimed at providing urban and resource constrained areas a means to access nutritious food as a human right, in a sustainable manner.

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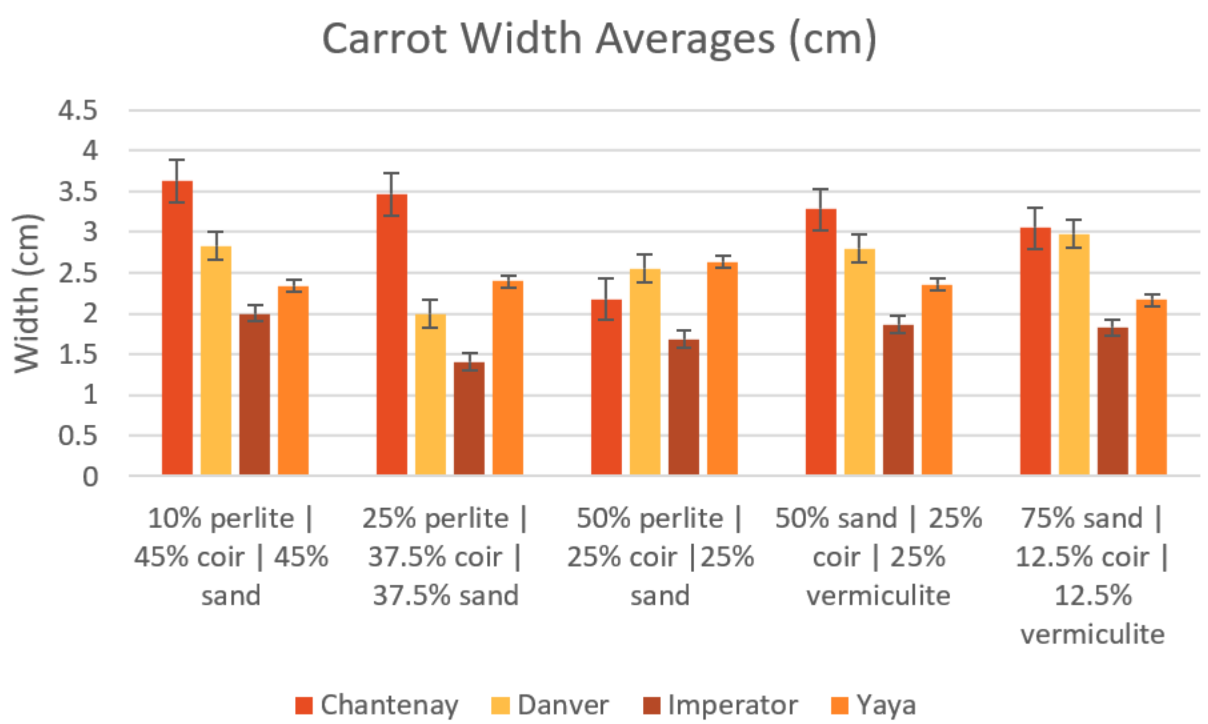
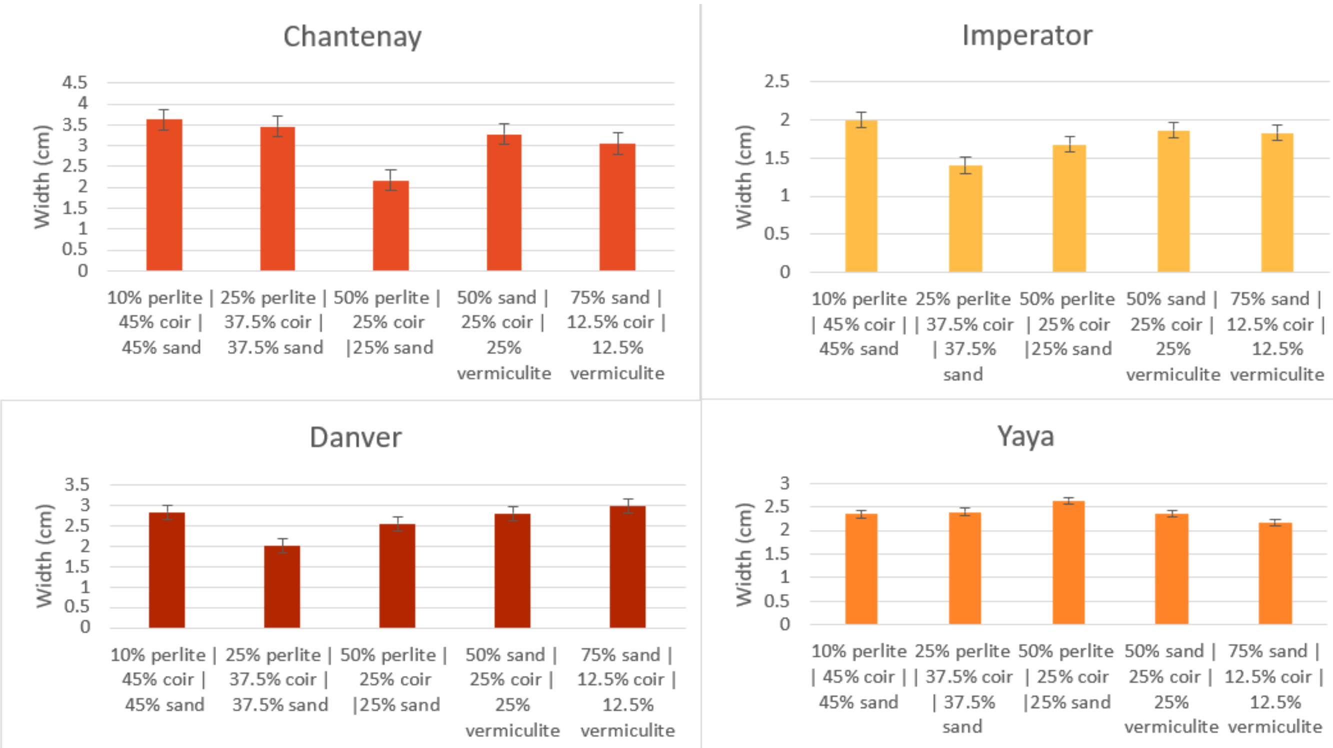
Appendix A. Carrot width averages across all four cultivars and five substrates

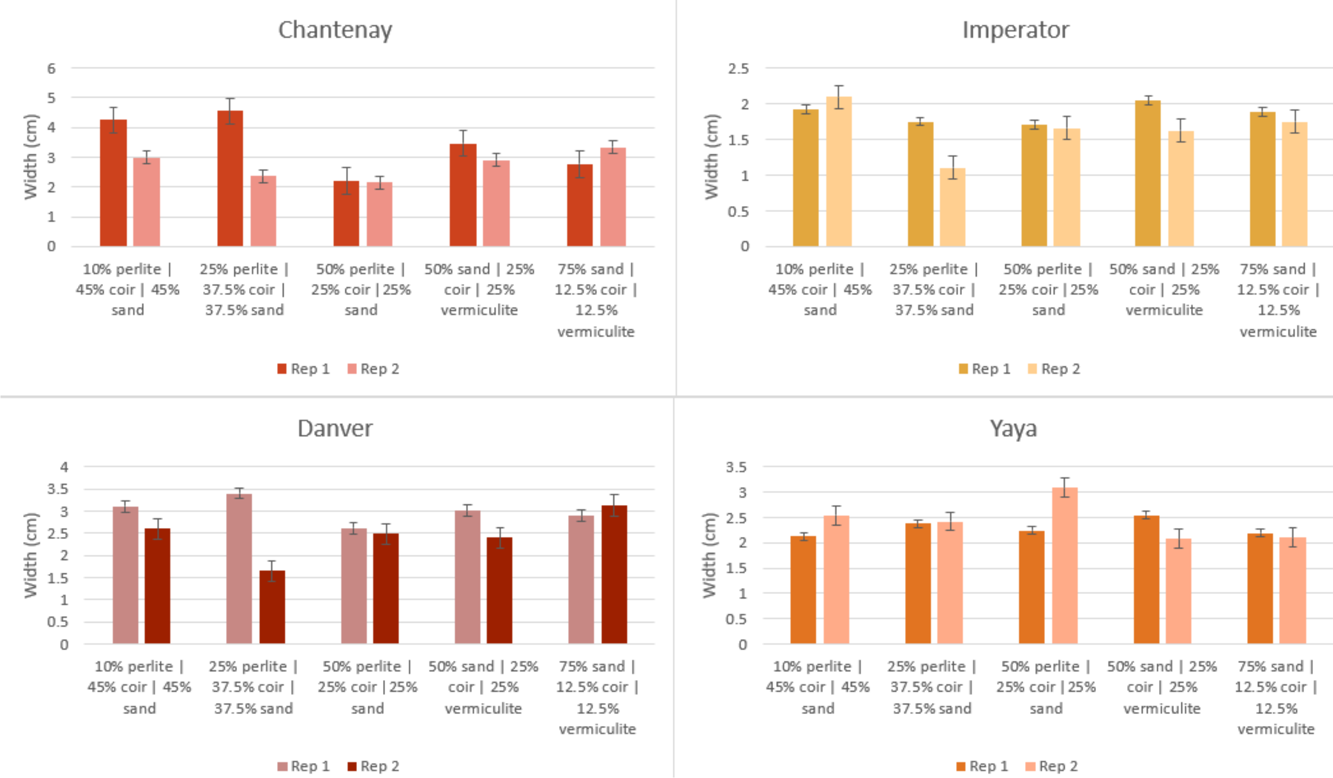
Raw data can be shared upon request at trinh074@umn.edu



Appendix B. Carrot width averages across all four cultivars



Appendix C. Carrot width averages between Rep 1 and Rep 2



Appendix D. Least Squares Means table for length based on medium factor. Blue numbers highlight large differences within sand or perlite dominated mediums.

Length Least Squares Means Table - Medium

Level	Least Sq Mean	Std Error	Mean
10% perlite	9.629028	0.42492031	10.2267
25% perlite	9.500868	0.39010765	9.8420
50% perlite	8.069221	0.36568145	8.5686
50% sand	10.473036	0.39564137	10.5905
75% sand	11.768899	0.43030608	11.4600

Appendix E. Least Squares Means table for length based on variety factor. Chantenay = 1, Danver = 2, Imperator = 3, Yaya = 4.

Length Least Squares Means Table – Variety

Level	Least Sq Mean	Std Error	Mean
1	8.044167	0.43948229	8.0735
2	9.330774	0.36576810	9.1327
3	10.410016	0.29451356	10.2667
4	11.767885	0.32179638	11.4843

Appendix F. Least Squares Means table for length based on medium*rep factor

Length Least Squares Means Table – Medium*Rep

Level	Least Sq Mean	Std Error
10% perlite,1	10.005556	0.60264255
10% perlite,2	9.252500	0.59920866
25% perlite,1	9.118056	0.60520518
25% perlite,2	9.883681	0.49240493
50% perlite,1	8.130903	0.52289128
50% perlite,2	8.007540	0.51134763
50% sand,1	10.241071	0.47951450
50% sand,2	10.705000	0.62943962
75% sand,1	10.366964	0.52570254
75% sand,2	13.170833	0.68138837

Appendix G. Least Squares Means table for fresh weight based on medium factor

Fresh Wt. Least Squares Means Table - Medium

Level	Least Sq Mean	Std Error	Mean
10% perlite	38.671528	2.9964134	35.6111
25% perlite	30.825347	2.7509248	27.6260
50% perlite	25.935813	2.5786783	26.4157
50% sand	37.950893	2.7899469	38.1429
75% sand	47.474554	3.0343923	42.1425

Appendix H. Least Squares Means table for fresh weight based on variety factor

Fresh Weight Least Squares Means Table - Variety

Level	Least Sq Mean	Std Error	Mean
1	42.411667	3.0991003	41.5618
2	38.590357	2.5792894	36.0442
3	21.602897	2.0768233	20.8292
4	42.081587	2.2692137	40.4514

Appendix I. Least Squares Means table for fresh weight based on medium*rep factor

Fresh Weight Least Squares Means Table – Medium*Rep

Level	Least Sq Mean	Std Error
10% perlite,1	46.151389	4.2496585
10% perlite,2	31.191667	4.2254438
25% perlite,1	40.147222	4.2677295
25% perlite,2	21.503472	3.4722952
50% perlite,1	24.908333	3.6872760
50% perlite,2	26.963294	3.6058735
50% sand,1	42.368452	3.3813956
50% sand,2	33.533333	4.4386236
75% sand,1	35.574107	3.7071002
75% sand,2	59.375000	4.8049510