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Article

Performance comparison of indoor polyculture utilizing hydroponic and soil-based systems

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SUMMARY

Due to the rapidly expanding human population, the agriculture industry has struggled to provide enough food to meet demand. This issue has prompted increased interest in new ways to make farming more efficient. One promising solution is hydroponic farming, a method of growing plants with a nutrient solution as the medium. In this study we examined hydroponics, and its potential applications in household agriculture. Among its various possible uses, one area that has not been thoroughly researched is hydroponic polyculture. In this study, we compared hydroponic polyculture (HP) with soil-based polyculture (SP). We hypothesized that the HP system would yield taller and more mature plants as hydroponic systems provide more direct nutrient delivery and greater water efficiency, and single-plant hydroponics have been shown to grow faster than soil-based systems. We planted five types of vegetable plants: pickling cucumber, Swiss chard, basil, cherry tomato, and lettuce. We measured the height of each plant in both systems for 60 days and on the last day we assessed plant maturity, defined as the presence of at least one mature leaf or flower/fruit. In contrast with our prediction, the SP plants grew significantly taller and were more mature than the plants in the HP system. These results suggest that soil-based farming may be more effective than hydroponic farming in the case of polyculture systems.

INTRODUCTION

The challenge of food production is a pressing issue, with over 713 million individuals currently experiencing chronic hunger (1). This problem is expected to intensify with projected population growth, as current agricultural practices are unlikely to meet future food demands due to the limited availability of arable land (2). By 2050, the global population is projected to reach 9.5 billion, yet in 2010, when the population was only 6.8 billion, approximately 80% of the world's arable land was already used for food production, meaning that feeding an additional 2.7 billion people would require an area of arable land comparable in size to Brazil, which is not currently available (2). Addressing this issue will require both refining existing agricultural methods and advancing new optimized farming technologies.

One promising solution to this issue is hydroponic farming. Hydroponic farming is a method of growing crops using nutrient -infused water as the medium rather than soil (3). It is used primarily in large-scale vertical farms, where environmental factors such as temperature, humidity, and many other factors are controlled using heaters, air-conditioners, humidifiers, dehumidifiers, and other equipment (4). These systems allow for greater artificial control of the plants, resulting in increased yield compared to traditional farming methods (4). Also, the indoor nature of hydroponic systems allows for more effective prevention of pathogens and biological contaminants compared to traditional soil farming (5). These advantages increase efficiency in hydroponics compared to soil-based farming for large-scale agriculture (4, 5). In addition, hydroponic systems are vertically stackable, which allows for significantly more crops to be grown in the same amount of horizontal land (6). However, its value in household agriculture has yet to be thoroughly evaluated.

Hydroponics may be most applicable to household farming (also referred to as household gardening), which is small-scale farming mainly for personal use and is typically done in or near one's household (7). However, household farming has its own limitations: for example, since it typically yields little to no profit, the budgets for these farms are significantly smaller than those of large-scale commercial farms. This limited budget, in turn, restricts factors such as resource allocation and the amount of land available for crop cultivation. These factors play a role in how effective hydroponic farming is. For example, since vertical space is as important as horizontal space with household farming due to ceiling heights and other space limitations, the ability to stack hydroponics vertically may prove less beneficial. Thus, efficiency is the determining factor of whether hydroponics would be beneficial to household agriculture. When evaluating the efficiency of household agriculture, several factors must be considered, including whether the garden is located indoors or outdoors and whether it will be a monoculture or polyculture system. Outdoor growing would be similar to industrial farms, where hydroponics would likely have greater efficiency than soil-based farming, assuming that the hydroponic system is placed in an enclosed structure with a controlled environment. This is because, as with commercial farming, with outdoor farming there is a designated area of land where either a hydroponic system or a soil-based farm can be built, with budget being the primary limiting factor. Indoor hydroponic farming, on the other hand, would be inside a house where factors like ceiling heights, environmental factor controllability, and space are limited. These factors cause indoor hydroponic systems to differ significantly from large-scale commercial farms. Another aspect to consider is how the system is going to be populated. Typically with indoor growing systems, there are two major types: monoculture systems (a system with one plant species) and polyculture systems (a system with multiple different species of plants) (8). Monoculture hydroponic systems are more efficient than monoculture soil systems in promoting

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faster growth and greater biomass (9). However, polyculture systems have not been evaluated yet.

In this study, we tested whether soil-based or hydroponic farming is more effective in polyculture systems. We grew five types of plants (pickling cucumber, Swiss chard, basil, cherry tomato, and lettuce) in both a hydroponic system and a soil system. We selected these plants based on how closely their pH, temperature, oxygen, alkalinity, and nitrogen requirements matched one another to ensure that the plants in the system were compatible. As hydroponics has outperformed soil-based farming in prior experiments, we hypothesized that the hydroponic polyculture (HP) system would yield plants with a greater height and more maturity than the soil polyculture (SP) system (9). However, our findings did not support this hypothesis, as the SP system plants grew taller than the plants grown in the HP system and demonstrated more signs of maturation (flowers or fruit for pickling cucumber and cherry tomato, and mature leaves for basil, Swiss chard, and lettuce) in comparison to the hydroponically grown plants. Here, we have shown that hydroponic farming may not always be a substitute for soil-based farming, especially in polyculture systems.

RESULTS

To evaluate whether the HP system produced taller plants than the SP system, we compared plant growth across both systems. For each system, we grew 45 plants, consisting of five different plant types (nine of each type): pickling cucumber, Swiss chard, basil, tomato, and lettuce. We controlled outside variables by placing the systems side-by-side and providing both systems with similar amounts of fertilizer and light exposure. As the plants grew, we took an image each day for 60 consecutive days and monitored the plants to determine whether their height decreased. If we visually observed a decrease in height, we measured the plant to ensure that we accurately recorded its maximum height regardless of wilting. On the final day, we assessed plant maturity based on the presence of flowers, fruit, or mature leaves, depending on species.

We found that the SP system plants had a substantially larger maximum height than the HP system plants, except in the case of lettuce (**Figure 1**). The heights of the soil plants, except for lettuce, were about three times that of the hydroponic plants. This difference was even more pronounced for the large plants like cherry tomatoes and pickling cucumber, with the soil-grown pickling cucumber plants having an average of nearly four times the height of the hydroponically grown counterparts (11.89 cm *vs*. 46.44 cm, $p < 0.05$, two-tailed *t*-test). The cherry tomato plants grown in the SP were on average approximately 28 times the height of their hydroponically grown counterparts (2.333 cm *vs*. 67.11 cm, $p < 0.05$, two-tailed *t*-test). Basil plants grown in the SP system were on average about three times taller than those grown in the HP system (2.444 cm *vs*. 6.222 cm, $p < 0.05$, two-tailed *t*-test). Similarly, Swiss chard plants grown in soil reached nearly three times greater heights than hydroponically grown plants (2.111 cm *vs*. 6.111 cm, $p < 0.05$, two-tailed *t*-test). In contrast, lettuce plants grown in the HP system had approximately two times greater mean height than those grown in the SP system (7.444 cm *vs*. 4.778 cm); however, this difference was not statistically significant ($p > 0.05$, two-tailed *t*-test).

We also observed and compared the maturity of plants across both systems using the number and percentage

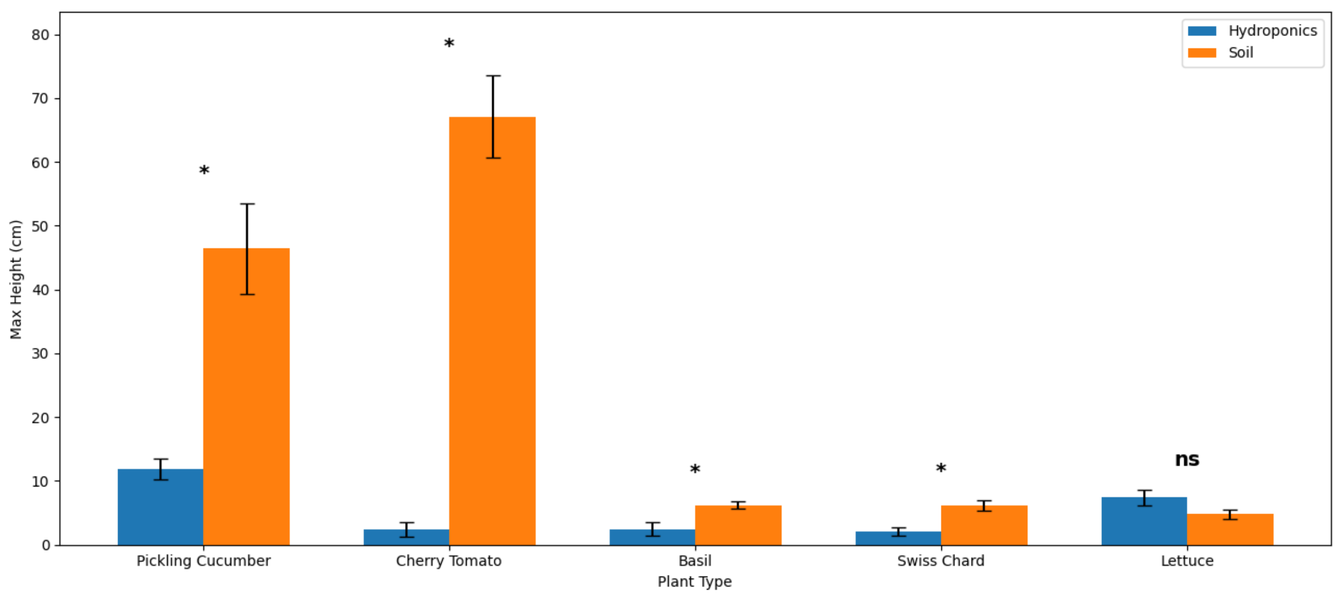

Figure 1: Mean Maximum heights of soil vs hydroponics systems. Mean maximum height ± SE (standard error) of basil, lettuce, cherry tomato, Swiss chard, and pickling cucumber plants grown in hydroponic (blue) and soil (orange) systems for 60 days. Each bar represents the average maximum height of nine plants per group. The basil, cherry tomato, Swiss chard, and pickling cucumber plants reached significantly greater heights in the soil systems compared to the hydroponic systems, while the lettuce plants showed no significant difference in maximum height between the two growing systems. Asterisks indicate that there is a statistically significant difference in average maximum heights between the two systems ($p < 0.05$), while "*ns*" indicates no significant difference, two-tailed *t*-test.

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Plant Type	System	Number of Mature Plants (out of 9)	Percentage of Mature plants	Maturity Indicator
Pickling Cucumber	Hydroponic	1	11%	Flowers present
	Soil	8	89%	
Cherry Tomato	Hydroponic	0	0%	Flowers present
	Soil	0	0%	
Basil	Hydroponic	2	22%	Mature leaves present
	Soil	9	100%	
Swiss Chard	Hydroponic	0	0%	Mature leaves present
	Soil	0	0%	
Lettuce	Hydroponic	5	56%	Mature leaves present
	Soil	2	22%	

Table 1: Maturity of Plants by Growing System: Number and percentage of plants showing maturity indicators (flowers or mature leaves) in hydroponic vs soil systems on day 60.

of plants that developed mature leaves or flowers (**Table 1**). Overall, soil-grown plants in the SP system displayed higher maturity than hydroponically grown plants in the HP system. Pickling cucumber plants grown in soil had eight of nine plants (89%) developing flowers, while only one hydroponic plant (11%) showed flowering. Basil exhibited the largest difference between systems, with all soil-grown plants (100%) developing mature leaves, compared to 22% of hydroponic basil plants. Swiss chard and cherry tomato did not produce mature leaves or flowers in either system during the experiment. Lettuce was an exception, as hydroponically grown lettuce showed a higher proportion of mature plants (56%) compared to soil-grown lettuce (22%), despite overall lower survival in the hydroponic system.

DISCUSSION

The goal of this study was to compare the growth of multiple plant species in HP versus SP systems. We hypothesized that plants in the HP system would have greater heights and be more mature than those in soil. Contrary to our hypothesis, the soil-grown plants grew significantly taller than the hydroponic plants in four out of the five species tested.

This outcome may be attributed to the nutrient buffering and retention in soil, which buffers nutrient availability through chemical retention and microbial cycling, reducing short-term fluctuations in nutrient supply (10). Hydroponic farming allows nutrients to go directly to the roots; however, since each of the different plants in the system has different nutrition requirements, the plants may not have simultaneously received the proper nutrient ratio required for optimal growth (11, 12). With the soil-grown plants, the ability of the soil to buffer nutrient availability may have mitigated this issue, allowing the plants to continue growing efficiently. Additionally, soil helps plants develop a stronger, more structured root system, as the roots grow and anchor into the soil. In contrast, plant roots are suspended in the nutrient solution for hydroponic systems. Plants with sturdier root systems are better able to support sustained shoot growth, so this may have played a role in our observation that growth in a hydroponic system produced plants that were shorter in height than those in a soil-based system (13). The difference in maturity may also be explained by how nutrient availability influences the plant's allocation of resources, since when nutrients are limited or unevenly accessible, plants tend to allocate available resources toward maintaining vegetative growth and basic physiological functions, delaying the transition to reproductive development until sufficient resources are available (14). In contrast, the soil-grown plants in our study may have experienced a more stable nutrient supply because of soil buffering and microbial nutrient cycling, allowing them to shift from the vegetative growth stage to reproductive maturity quicker (10, 15).

We also observed that the magnitude of the mean difference in growth was less for the greens and herbs than that of the pickling cucumbers and cherry tomatoes (Figure 1). This outcome may be because larger plants like pickling cucumbers and cherry tomatoes use more nutrients than greens and herbs (16, 17). Since the current study aimed to promote optimal growth of all the plants in the system, the fertilizer nutrient ratio was not individualized for each plant; therefore, the ratio used may not have been optimal for pickling cucumbers and cherry tomatoes. In soil systems, however, not tailoring fertilizer ratios for each plant may matter less; since the nutrients in the system are naturally redistributed, the plants that require higher fertilizer levels are able to access the nutrients they need, while plants with lower nutrient demands can avoid over-fertilization.

It was also observed that the Swiss chard and cherry tomato plants did not mature throughout the duration of the experiment. This could be attributed to the length of the experiment. The typical time from germination to flowering

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of a cherry tomato plant is approximately 20–30 days for the appearance of the first flower, with substantial genetic and environmental variability causing some genotypes to flower earlier and others after 30 days (18). In fact, the seed packet says approximately 65 days to harvest and considering the fact that it takes around 20–30 days for fruit to grow from a flower, this should have meant that the plants should have flowered before 60 days under optimal growing conditions (18). However, that was not the case during the experiment. The same was true for Swiss chard, where seeds typically germinate in about 5–14 days, and vegetative leaves reach small harvestable size around 30–45 days after sowing, and the seed packet indicated that they should be ready for harvest in approximately 30–60 days (19). Nevertheless, after the experiment it was observed that a couple of the cherry tomato plants flowered around 2–3 days after the experiment and did grow fruit, so although the length of the experiment made sense based on the expected growth times of the plants, it may not have been long enough to truly gauge a comparison between growth of cherry tomato and Swiss chard plants in the HP and SP systems considering none of the plants reached maturity at the study even though the SP system plants were close to maturity.

It must be noted that there were some limitations in this experiment. First and foremost, the experiment was limited to 60 days which as stated above could have affected the max growth height and maturation of the plants. However, considering that most plants were expected to have been ready to harvest by around the 60-day mark, it should not have been an issue, especially since only mature plants produce fruit, and fruit takes around 20 days to be ready to be harvested. In fact, based on the seed packets basil had the only harvest time not near 60 days, with a harvest time of 85 days, and 100% of the SP basil plants had reached maturity and 22% of the HP basil plants had reached maturity by the end of the experiment. Another limitation was that the experiment involved 90 plants, which meant that daily measurements of each plant were not feasible, as there was no advanced technology used; therefore, the decreasing plant height method was used to estimate maximum growth. This could have led to a slight difference between the true max heights and actual max heights of the plants; however, every plant received the same treatment, and the difference would be so small that it was unlikely to alter the overall conclusions given the magnitude and consistency of observed differences.

In this study, we aimed to determine whether HP systems produce taller and more mature plants than SP systems in household settings. As plants in the soil-based system were able to grow taller, more mature plants, our results did not support the hypothesis that the hydroponics system would lead to improved growth. Ultimately, the results of this study highlight that soil farming could be more efficient than hydroponics for polyculture systems. While hydroponic farming demonstrates high efficiency across many applications, this study suggests that soil-based methods may still outperform hydroponics under certain conditions.

These findings also highlight the need for further research to delineate the contexts in which hydroponic systems offer clear advantages versus those where traditional soil-based approaches remain more effective. Specifically, considering that soil-based farming fared significantly better than hydroponic farming in this study, the underlying causes of this difference need to be determined by isolating individual variables. Future studies would need to investigate whether soil buffering and microbial nutrient cycling were the key factor, whether hydroponic systems can be modified to provide distinct nutrient levels tailored to each plant species in a polyculture setup, and how hydroponics could be optimized for polyculture household farming. Additionally, repeating this study using plants with similar nutrient requirements could help control for differences in nutrient demand, while directly observing nutrient distribution in hydroponic systems would provide insight into how nutrients are absorbed and whether certain plants are disadvantaged. Ultimately, these results suggest that no single farming method may be universally optimal, and that the choice between hydroponic and soil-based systems likely depends on specific environmental conditions, resource constraints, and production goals.

MATERIALS AND METHODS

Creating the Growth Systems

For the HP system, we constructed a 54-site hydroponic system using PVC pipes, a 5-gallon bucket for water storage, water pretreated with 20 mL of fertilizer (3-1-2 NPK ratio fertilizer), and a 10-watt water pump attached to a timer (**Figure 2**). For the SP system, we filled a large pot (7,475 cm^2) with Miracle-Gro raised-bed soil mixed with Black Kow cow manure and homemade compost (**Figure 3**). We created an overhead white light system using a metal rack and a grow light connected to a timer system. We placed both of these systems side-by-side under the overhead light system in a way that ensured full light coverage for both systems.

Seeds

We used five types of Ferry-Morse non-GMO seeds: pickling cucumber (*Cucumis sativus*, Ferry-Morse), Swiss chard (*Beta vulgaris subsp. cicla*, Ferry-Morse), basil (*Ocimum basilicum*, Ferry-Morse), Black Seeded Simpson

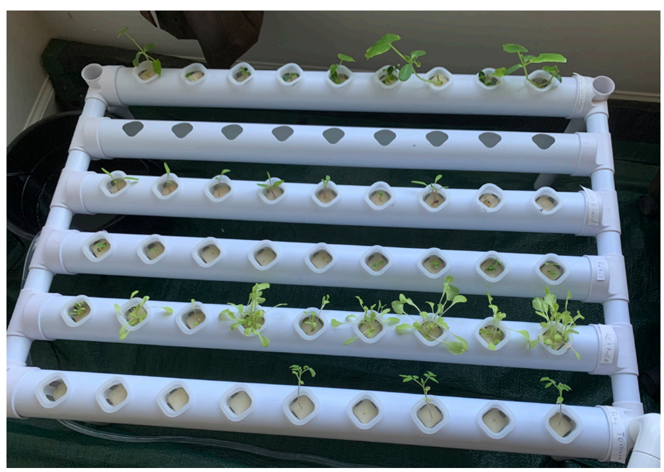

Figure 2: Hydroponic polyculture system. Image of the HP system on day 24. The system consists of 54 sites; however, only 45 sites were used in this study, as the second-from-top row was not used. Each row contained a different plant species, with pickling cucumber plants in the back, followed by Swiss chard, basil, lettuce, and finally cherry tomato plants in the front.

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Figure 3: Soil-based polyculture system. Image of the SP on day 17. Plants were put in rows based on plant type (this image includes only the plants that had fully germinated by day 17, meaning that the majority of the Swiss chard, basil, and pickling cucumber plants were not yet in the pot when the photo was taken).

lettuce (*Lactuca sativa*, Ferry-Morse), and Supersweet 100 VF Hybrid tomato (*Solanum lycopersicum var. cerasiforme*, Ferry-Morse). In general, we planted 18 seeds of each plant type, with 9 grown hydroponically and 9 in soil. However, for lettuce, basil, and Swiss chard, we planted three to five seeds per planting site, a common gardening practice to increase the likelihood of germination. However, by the end of the study, only one or two healthy plants emerged in each planting site.

Maintaining the Systems

We allowed the hydroponically-grown seedlings to germinate in small pockets within thoroughly moistened sponges, while the soil-grown seedlings germinated in either water (pickling cucumber, and Swiss chard) or wet tissue (basil, lettuce, and cherry tomato). When a sprout had extended out from the seed in both the hydroponic seedlings and the soil-grown plants, we shifted them into either the hydroponic system or the full-sized pot with soil. By day 20, both systems were completely filled with all 45 germinated plants. We monitored both systems daily to ensure the plants received sufficient nutrition. Each system received one scoop of fertilizer (3-1-2 NPK ratio fertilizer) every three days. Also, we monitored the pH daily and adjusted it if it fell outside the optimal range of 5.5–6.5, using dilute phosphoric acid to lower pH or dilute potassium hydroxide to raise pH, as needed to maintain nutrient availability (11, 20). As a safeguard, if the majority of the plant's leaves looked unhealthy, the frequency was increased or decreased in all systems based on the type of nutrient deficiency or over-sufficiency (21). The unhealthiness of a plant was determined based on observable changes in leaf shape and color, including chlorosis (uniform or interveinal yellowing), necrosis or browning of leaf margins, purpling of older leaves, leaf curling or deformation, and reduced leaf size (11, 22). Every 2 weeks, we completely replaced water in the hydroponic system to maintain a proper nutrient balance and prevent buildup of salts and microbial contaminants.

Data Collection

The vertical height of each plant was used as the main parameter of growth because it was easily quantifiable, and because the time frame of the study was too short for substantial horizontal growth. Each day we took an image at around 12 PM ET and monitored to observe a decrease in height. If a decrease in height was observed, we measured the height of said plant to ensure that its maximum height was recorded, regardless of wilting. If the plant subsequently grew taller than the previous measurement, we would record the new maximum height following the same procedure. For plants in our soil-based system, we measured the height from soil to the highest point. For plants in our hydroponic system, we measured the height from the point where the root became a shoot system to the highest point. In both systems, if the plant was wilted, we stretched it slightly to obtain an accurate measurement. We repeated these measurements for 60 days. We compared the maximum height measurements using a two-tailed t-test, with $p < 0.05$ representing statistical significance.

On the final day of the study (day 60) we assessed the plant maturity for all the plants in the study. Maturity was defined as the presence of at least one mature leaf or flower/fruit, depending on the species. For pickling cucumber and cherry tomato, we examined each of the nine plants for the presence of flowers or fruit. For basil, Swiss chard, and lettuce we deemed it mature if it had at least one leaf that was fully expanded beyond the early juvenile stage and exhibited the characteristic size/shape of a mature vegetative leaf. We then converted the number of mature plants for each species in each system into a percentage out of nine plants (**Table 1**).

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