Growth Response of Lactuca sativa L. (Lettuce) and Solanum lycopersicum (Tomato) to High pH Levels in a Nutrient Film Technique Hydroponics System

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Abstract

This study investigates the impact of high pH levels on the growth of *Lactuca sativa L.* (lettuce) and *Solanum lycopersicum* (tomato) in a Nutrient Film Technique (NFT) hydroponics system. Two identical NFT systems were designed, one serving as the control (pH ~7.35) and the other as the experimental group, where pH was reduced to ~6.5 using vinegar, compared to typical hydroponic systems where the pH is about 5. Over 40 days, the biomass of both lettuce and tomato plants and the pH levels of the nutrient solutions were recorded. Results indicate that lettuce in the system with reduced pH exhibited significantly greater biomass and growth rates than the control. The tomato plants also showed faster growth in the experimental system, although the results were less consistent. This study highlights the critical role of pH management in hydroponic systems, suggesting that slight reductions in pH can enhance plant growth, particularly in leafy greens like lettuce. Future research should explore pH optimization for different crops and environmental conditions to improve hydroponic efficiency.

1. Introduction

The rise of the Industrial Revolution in the 18th and 19th centuries led to the development of mechanized farm equipment and advancements in agricultural science that made mono-crop agriculture possible. Mono-crop agriculture, a farming practice where a single crop is grown on the same land year after year, has become a significant environmental concern. This high-productivity method is often used in large-scale industrial farming to maximize efficiency and yield for specific crops like wheat, corn, or soybeans. Unfortunately, the method also depletes soil nutrients, increases vulnerability to pests and diseases, and requires heavy chemical fertilizers and pesticides [1]. The lack of crop diversity in mono-cropping can negatively impact soil health and the surrounding ecosystem, making it imperative to explore sustainable alternatives [2].

Hydroponics is a more sustainable alternative to mono-cropping. It demands significantly less water and energy than traditional agricultural methods and yields higher total crop mass per square meter. Additionally, hydroponics is more environmentally sustainable as its lack of soil-based fertilizers prevents the introduction of nitrogen and phosphorus into the ecosystem [3]. This study aims to understand the effects of a high-pH nutrient solution on the growth of plants in hydroponic systems.

2. Literature Review

This literature review explores current research surrounding hydroponics systems, specifically the effect nutrient pH has on plant growth. This review aims to identify critical variables that influence the development of leafy greens and tomato plants in hydroponic systems. Additionally, it will compare the efficiency of various hydroponic systems.

2.1 Comparing Systems

Edokpolo [4] compared the efficiency of vertical and horizontal hydroponics systems in growing leafy greens in outdoor conditions and found that vertical systems produced an overall higher edible biomass. Conversely, in a later study, Edokpolo found that horizontal systems produced higher-growing plants, resulting in a better yield per square meter and more energy-efficient and cost-effective. Furthermore, Walters and Currey [5] compared the efficiency of two horizontal hydroponic systems, NFT and Deep Water Culture (DWC). The two systems had a negligible difference in total biomass production, but basil cultivar selection significantly impacted the final yield.

2.2 pH Levels on Plant Growth

Nutrient solution pH level is a significant variable in determining a plant's ability to thrive in hydroponic systems. When comparing the effects of low pH on hydroponic nutrient uptake, Gillespie et al. [6] found that decreased pH led to reduced concentrations of P, Ca, Mg, S, B, Mn, and Zn in leaves, while K and Al increased. N, Fe, Cu, Mo, and Na concentrations remained unaffected by pH changes. They also found that root damage was significantly higher in plants grown at pH 5.5 inoculated with *Pythium aphanidermatum,* a soil-borne plant pathogen, than in plants grown at pH 4.0 [6]. According to a study by Koehorst et al. [7], the growth and chlorophyll content of *Artemisia afra* (African Wormwood) is significantly affected by the pH of the water supplied, with optimal results occurring around pH 6.5. Both highly acidic and alkaline conditions negatively impact the fresh and dry weight, as well as the chlorophyll content, of the plant. In addition to pH levels, recent studies have analyzed the effect of different nutrient replacements on hydroponic plants. A study (Elisa Solis-Toapanta et al. [8]) on hydroponic tomatoes found that biweekly nutrient solution replacements led to healthier plants, greater fruit yield, and fewer issues like blossom-end rot, a common physiological disorder that causes a large dark, dry area to form at the bottom of the fruit. At the same time, simple fertilizer additions resulted in nutrient imbalances, reduced leaf area, delayed fruit ripening, and lower fruit weight, highlighting the need for specialized growing strategies for different conditions [8].

2.3 Gaps in Research

While several studies have examined the impact of pH on plant growth and compared the efficiency of hydroponic systems against conventional soil-based systems, more research is still needed to compare the efficiency of multiple other hydroponic systems. Additionally, there is not much research on the effect of external environmental factors on outdoor hydroponics, which remains largely unexplored. A possible reason is the inability to control some variables that may significantly impact the experiment.

Building on the research of Gillespie et al. (2020), this study aims to examine the effects of pH variations in NFT systems on both lettuce and tomato plants. By addressing the specific gap in understanding the impact of pH levels in outdoor environments, this research contributes to optimizing hydroponic practices in real-world conditions.

3. Design

The goal was to develop a practical and efficient hydroponics system to effectively measure the effect of differing pH levels. Initially, a budget of $200 was set for the entire project, including prototype designs and data gathering. The design must also fit within a 6ft x 6ft x 6ft space, as it will be constructed in a backyard.

Multiple designs were compared using YouTube videos and general online research to begin the process. Candidate designs were organized in a Pugh chart to compare their traits, such as complexity, space required, and cost. The NFT design is efficient with water and nutrient usage but requires constant attention to prevent pump failures, which can lead to drying plant roots. The DWC is simple to set up and provides highly oxygenated water, but this requires constant aeration and temperature monitoring. The Ebb and Flow (Flood and Drain) method provides good aeration as the roots are routinely exposed to air between draining cycles, leaving the system prone to pump or timer malfunctions. The drip system slowly drips out nutrient solution onto the base of each plant, allowing complete control over nutrient delivery and making it highly customizable, with the risk of clogging drip emitters with waste. Aeroponics suspends plants in the air with exposed roots, which are then regularly misted with nutrient solution. While this system maximizes oxygen availability, it also requires precise control over pump and misting systems, leaving it vulnerable to malfunctions. The Wick System allows plants to draw nutrients up a wick (cotton, felt) via capillary action from a reservoir, making it simple and passive with no moving parts. However, capillary action is limited, making it less suitable for larger plants that require more nutrients and water. The Kratky method places plants in a container with nutrient solution, exposing the roots to air as the water level drops. No pumps or moving parts are needed, but scalability is limited because each plant requires constant monitoring. Vertical Hydroponics grows plants in vertical columns or towers, with the nutrient solution being delivered to the top via a pump and trickling down through the medium or roots. It is very space efficient but requires a good understanding of water distribution due to the potential of uneven nutrient delivery.

Table 1: Pugh chart comparing aspects of different hydroponic systems

	Simplicity	Affordability	Efficiency	Space	Cost to Operate	Modularity	*Sum Total*
NFT	5	5	8	7	5	8	38
DWC	7	7	7	3	7	5	36
Wick System	9	1	3	4	8	3	28
Kratky Method	8	8	4	2	9	2	33
Flood / Drain	4	4	7	5	5	6	31
Drip	3	4	8	6	4	7	32
Vertical	2	3	9	10	3	9	36
Aeroponics	1	1	10	8	1	9	30

The system was based on an NFT design because it is highly modular and can expand by adding more channels or tiers. It is relatively efficient with floor space due to its ability to stack channels vertically while maintaining maximum yield. Compared to the other designs, the NFT system is moderately priced as it only requires pumps, channels, and a basin, though the cost increases with added size and complexity. It requires moderate attention to prevent occasional pump failures and leakage. Additionally, it is highly efficient with smaller plants with shallow roots, as the continuous nutrient flow supports rapid growth. However, larger plants may outgrow the shallow trough system.

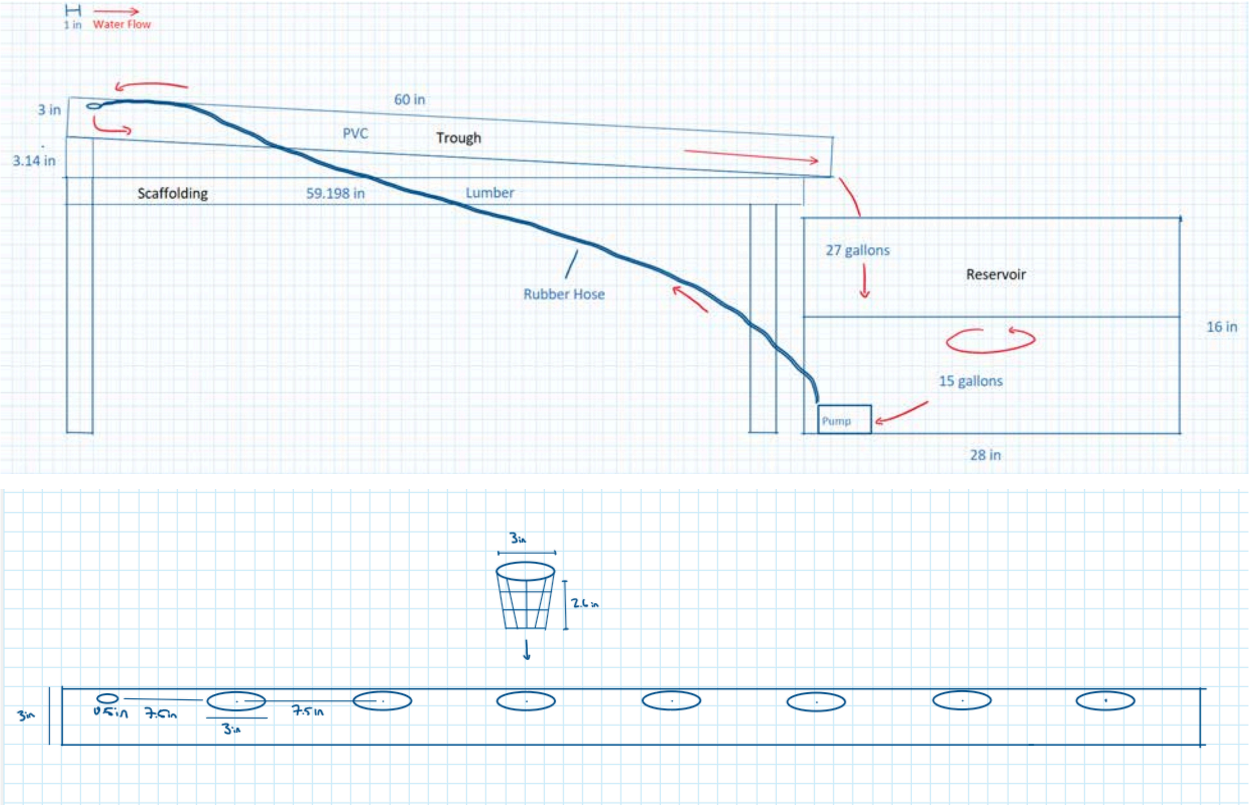


Figure 1: Schematic drawing of NFT hydroponic system. The PVC pipe was fastened to wooden scaffolding to act as the trough. A ½ inch rubber hose was fed through the inlet at the top and sloped at 4 degrees to allow water to flow into the reservoir. A pump at the bottom of the reservoir cycled the water back to the top of the trough.

Figure 2: Image of the built system

The final design consisted of four 4 inch PVC pipes that serve as the water channels. The water channels rest on supports made from readily available wood, PVC, or aluminum scaffolding. Channels were sloped at a 3 degree angle with 3 inch diameter holes drilled 7.5 in apart. In the end, there is a 27 gallon basin for the nutrient solution and a 140 GPH pump attached to a ½ inch rubber hose that feeds to the inlet of the water channel, creating a closed circuit. The 3 inch diameter net pots containing plant sprouts will be placed in the drilled holes. The pot height leaves ½ in from the bottom of the water channel to promote root growth.

3.1 Construction

Appendix A2 contains the complete list of materials. First, the 10 ft PVC pipe was sawed in half. Then, the measuring tape and marker were used to mark dots at 7.5 intervals along the now 5-ft PVC pipe's length. A circular hole saw was attached to the power drill and drilled 3-inch diameter holes using the markings as the center point.

17.5 inches of 2x4 lumber was measured for the scaffolding and was sawed off, repeating the process with the second leg. Then, 59 inches of lumber was measured and sawed off to create the body of the scaffolding. Then, 3.1 inches of lumber was measured to act as the incline. Wood glue was applied to the end of the legs and attached to the larger length of wood, one at the very left end and one about 10 inches from the right end. Glue was then applied to the end of the 3-inch piece and attached to the top of the left end of the wood base. It was aside to cure.

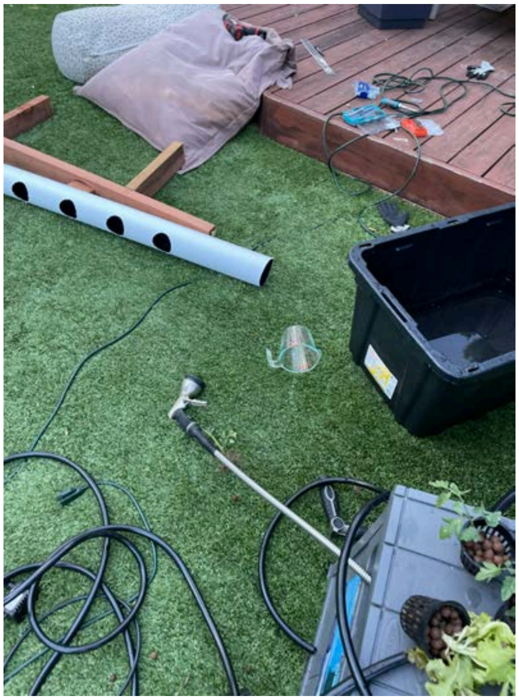


Figure 3: Progress while building the hydroponic system

Netting was not included in the original design but was added later because deer became an issue.

4. Methods

The initial design employed an NFT system with a singular channel feeding six slots—three for lettuce and three for tomato branches. Water was sourced from a garden hose and circulated using a 240-gallon per hour (GPH) fountain pump. The pH sensor used had an accuracy of ±0.1. In preparation for the experiment, the tomato samples were removed from the soil, and their roots were carefully washed with a garden hose. The plants were then placed in 3-inch diameter net pots, and the remaining space in each pot was filled with Leca clay pebbles to support and aid in water retention.

During the initial phase, the plants did not have sufficient time to establish their root systems, resulting in death. Over the first five days, temperatures ranged from a high of 88°F during the day to a low of 54°F at night. By the fifth day, most of the lettuce plants had dried up due to heat stress, and the remaining tomato plants were eaten by deer due to the system's compromising position in the backyard. Therefore, a new experiment was started with the same setup procedure and the addition of netting.

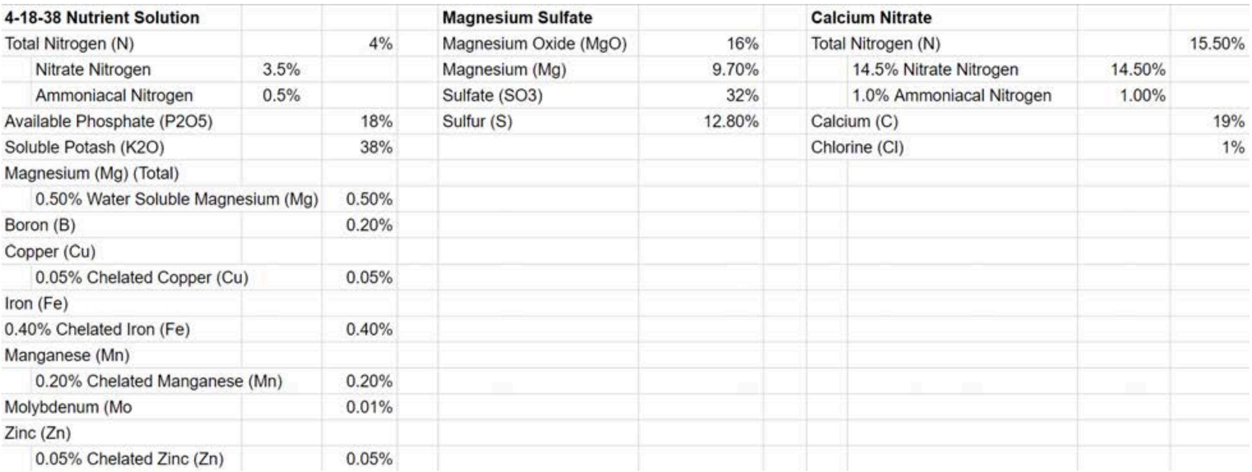
The system was moved to the east side of the house, out of direct sunlight during the day, to prevent the plant roots from drying up too quickly. The slope of the trough was decreased to 2 degrees. A second identical NFT system was also constructed to house the experimental group. To prevent future wildlife interference, bird netting was installed around both systems. The netting was made of plastic mesh wrapped around supporting pillars constructed from leftover lumber. The nutrient solution was switched from Haligo Hydroponic Plant Food to Masterblend, PowerGrow, and vinegar for more accurate nutrient and pH predictions.

The experimental phase was conducted on the east side of the backyard, under partial shade from the main house. The experiment was conducted with two identical NFT systems with two nutrient solutions (unaltered and adjusted with vinegar, as described later). The independent variable being manipulated is the pH level of the nutrient solution. The dependent variable being measured is the biomass of the tomato and lettuce plants. The design is identical between system A and system B. System B was the control group, where the pH level was not altered with vinegar, leaving it at about 7.36. System A was the experimental group, where the pH level was altered with vinegar to reduce it to about 6.47.

In each NFT system, six plants were grown–three lettuce and three tomato seedlings. The lettuce and tomato seedlings were placed in alternating order. Each NFT system contained 20 gallons of nutrient solution made using municipal water. Additionally, the nutrient solution for both systems was replaced on days 6, 14, and 30.

The baseline nutrient solution featured 24 grams of nitrogen, phosphorus, and potassium nutrient blend mixed with 12 grams of Magnesium Sulfate in 2 gallons of warm water before adding Calcium Nitrate. Elemental concentrations are shown in Table 1. Before transplant, system A nutrient solution pH was adjusted to 6.5 using white vinegar. The pH of system A was monitored every other day and adjusted to maintain a range of ±0.3 from the target pH. The pH of system B was also recorded but not adjusted.

Table 2: Elemental composition of fresh nutrient solutions



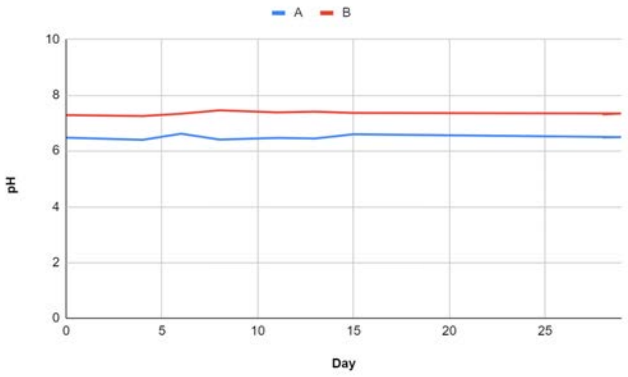
4-18-38 Nutrient Solution			**Magnesium Sulfate**		**Calcium Nitrate**		
Total Nitrogen (N)		4%	Magnesium Oxide (MgO)	16%	Total Nitrogen (N)		15.50%
Nitrate Nitrogen	3.5%		Magnesium (Mg)	9.70%	14.5% Nitrate Nitrogen	14.50%	
Ammoniacal Nitrogen	0.5%		Sulfate (SO3)	32%	1.0% Ammoniacal Nitrogen	1.00%	
Available Phosphate (P2O5)		18%	Sulfur (S)	12.80%	Calcium (C)		19%
Soluble Potash (K2O)		38%			Chlorine (Cl)		1%
Magnesium (Mg) (Total)							
0.50% Water Soluble Magnesium (Mg)		0.50%					
Boron (B)		0.20%					
Copper (Cu)							
0.05% Chelated Copper (Cu)		0.05%					
Iron (Fe)							
0.40% Chelated Iron (Fe)		0.40%					
Manganese (Mn)							
0.20% Chelated Manganese (Mn)		0.20%					
Molybdenum (Mo		0.01%					
Zinc (Zn)							
0.05% Chelated Zinc (Zn)		0.05%					

Plants were individually removed from the system on specified days during the experiment (dates detailed below), and dry mass was recorded. Lettuce plants were measured to 0.01 grams, but due to technical weight limitations, the tomato plants were weighed to within 1 gram. Once the dry mass was recorded, a photo was taken of the plants against a white backdrop with indicators every inch for scale. The plants were then placed in the original slots in the system. An 8 oz sample of nutrient solution from both systems was removed and tested for pH using an Arduino liquid pH sensor (code below conclusion). Once the pH was recorded, vinegar was added to the solution sample from System A until the pH reached about 6.5 ±0.3. Approximately 320x the amount of vinegar added to the sample was then added to the main reservoir of System A.

5. Results

The pH of the nutrient solution in both systems varied greatly throughout the experiment. Only the pH of system A was adjusted to 6.5.

Table 3: System pH levels for each day.



There was a significant difference in growth between the lettuce in System A and the lettuce in System B. From the beginning, the lettuce in System A displayed marginally quicker growth, which then shot up around day 11 of the experiment, as shown in Fig. 3.

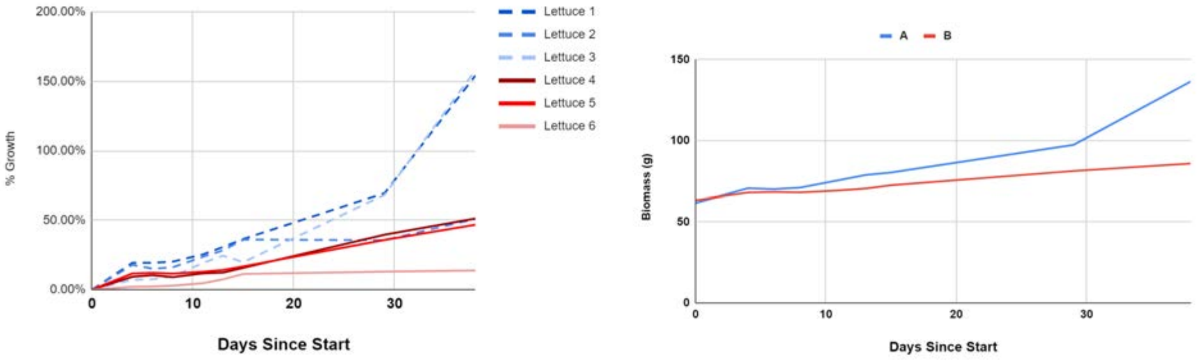


Figure 3: Left, individual lettuce biomass over time. Right, mean biomass for systems A and B over time.

As shown in Fig. 4, the mass of the tomato plants followed a similar trend to the lettuce, where the growth in both systems remained similar for the first few days until about day 10, when the plants in System A began to grow much faster. Due to experimental difficulties explained in the conclusion, Tomato 6 was removed from the calculations.

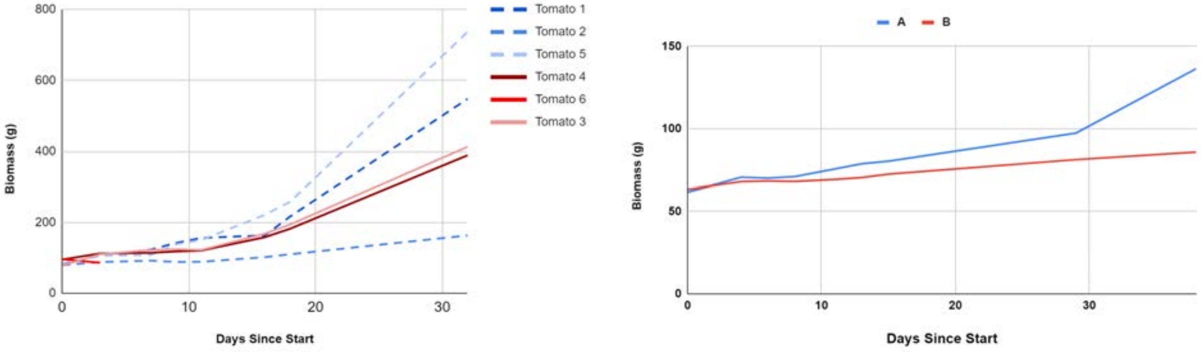


Figure 4: Left, Individual tomato biomass over time. Right, Mean tomato biomass for Systems A and B over time.

The relative growth percentages were much higher for the lettuce in System A throughout most of the experiment, significantly increasing toward the end. In contrast, the lettuce in System B remained approximately constant, as shown in Fig. 5. The final mean relative growth for the lettuce in System A was much higher than that in System B. However, the standard deviation was also much higher.

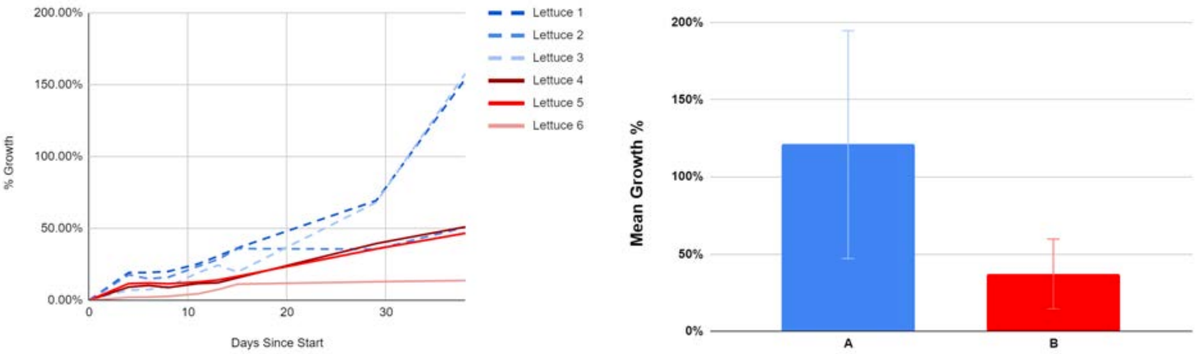


Figure 5: Left, Lettuce relative percent growth over time. Right, Lettuce final relative growth for Systems A and B

	Day 7	Day 9	Day 11	Day 13	Day 15	Day 38
Lettuce 1						

Figure 6: Lettuce 1 growth over time.

Conclusion

The primary objective of this study was to determine the impact of reduced pH levels on the growth of tomato and lettuce plants using a Nutrient Film Technique (NFT) hydroponics system. The results showed that System A, with a pH level of 6.5 ±0.3 overall, produced a higher lettuce biomass than System B, with an unaltered pH of about 7.35. Additionally, the relative percent growth from the beginning of the experiment was much higher in System A than in System B. However, tomato growth was not as consistent, with only two plants in System A exhibiting massive growth over those in System B.

These findings suggest that lower pH levels are more effective for promoting growth in lettuce. However, its effect on tomato plants requires further research. A possible explanation for this anomaly is the interference of wildlife in the experiment. Between days 3 and 7, neighboring crows bypassed an opening in the netting. They removed Tomato Plant 6 from its slot in System B. Any calculations excluded Tomato Plant 6 from all mean evaluations. Similarly, wildlife removed a large portion of biomass from Tomato Plant 2 before conducting the experiment. The experiment proceeded as planned, and a new baseline biomass was set for Tomato Plant 2. The weather throughout this experiment varied frequently between day and night, potentially causing inconsistencies in lettuce growth.

Future experiments should include a more controlled environment to prevent external interference. Another limitation of this experiment was the size of both systems. Towards the end of the experiment (after day 16), the roots of the tomato plants in both systems began to restrict water flow through the trough, potentially causing uneven nutrient distribution between lettuce and tomato plants. Future research could explore the effects of a broader range of pH levels and use different hydroponic systems, such as Deep Water Culture (DWC), to determine their effectiveness under varying environmental conditions. This study provides valuable insights into optimizing pH levels in hydroponic systems for enhanced plant growth, contributing to more efficient and sustainable agricultural practices.

Author Contributions: Jared Lee* and Nathan Hendradi* constructed both hydroponic systems. Jared Lee designed the experiment, performed the experiment, performed measurements, and analyzed the data. Jared Lee and Nathan Hendradi wrote the literature review. Jared Lee wrote the abstract, introduction, and documented the experimental process.

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Appendix

A1: Arduino Sensor Code

```
/*
 # This sample code is used to test the pH meter V1.0.
 # Editor : YouYou
 # Ver    : 1.0
 # Product: analog pH meter
 # SKU    : SEN0161
*/
#define SensorPin A0            //pH meter Analog output to Arduino Analog Input 0
#define Offset 0.00            //deviation compensate
#define LED 13
#define samplingInterval 20
#define printInterval 800
#define ArrayLenth  40    //times of collection
int pHArray[ArrayLenth];   //Store the average value of the sensor feedback
int pHArrayIndex=0;
void setup(void)
{
  pinMode(LED,OUTPUT);
  Serial.begin(9600);
  Serial.println("pH meter experiment!");    //Test the serial monitor
}
void loop(void)
{
  static unsigned long samplingTime = millis();
  static unsigned long printTime = millis();
  static float pHValue,voltage;
  if(millis()-samplingTime > samplingInterval)
  {
      pHArray[pHArrayIndex++]=analogRead(SensorPin);
      if(pHArrayIndex==ArrayLenth)pHArrayIndex=0;
      voltage = avergearray(pHArray, ArrayLenth)*5.0/1024;
      pHValue = 3.5*voltage+Offset;
      samplingTime=millis();
  }
  if(millis() - printTime > printInterval)   //Every 800 milliseconds, print a numerical, convert the state of the LED indicator
  {
    Serial.print("Voltage:");
        Serial.print(voltage,2);
        Serial.print("    pH value: ");
    Serial.println(pHValue,2);
        digitalWrite(LED,digitalRead(LED)^1);
        printTime=millis();
  }
}
```

```
double avergearray(int* arr, int number){
  int i;
  int max,min;
  double avg;
  long amount=0;
  if(number<=0){
    Serial.println("Error number for the array to avraging!/n");
    return 0;
  }
  if(number<5){   //less than 5, calculated directly statistics
    for(i=0;i<number;i++){
      amount+=arr[i];
    }
    avg = amount/number;
    return avg;
  }else{
    if(arr[0]<arr[1]){
      min = arr[0];max=arr[1];
    }
    else{
      min=arr[1];max=arr[0];
    }
    for(i=2;i<number;i++){
      if(arr[i]<min){
        amount+=min;        //arr<min
        min=arr[i];
      }else {
        if(arr[i]>max){
          amount+=max;    //arr>max
          max=arr[i];
        }else{
          amount+=arr[i]; //min<=arr<=max
        }
      }//if
    }//for
    avg = (double)amount/(number-2);
  }//if
  return avg;
```

A2: Materials Used

Item	**Quantity**	**Price**	**Total Price**	**Purchase Link**
3 in. x 10 ft. Triplewall Solid Drain Pipe	1	$17.76	$17.76	Advanced Drainage Systems 3 in. x 10 ft. Triplewall Solid Drain Pipe 3550010 - The

				Home Depot
Net Pots	1	$11.00	$11.00	CHTASO 50 PCS 3 Inch Heavy Duty Net Pots,Hydroponic Cups,Garden Slotted Mesh Net Cups,Plant Nursery Net Pots for Hydroponics
LECA Clay Pebbles	1	$8.99	$8.99	Amazon.com : Malifea 2LBS Leca Expanded Clay Pebbles Hydroponics Supplies for Indoor Garden Plants (2LBS)
Tomato Sprouts	9	$4.98	$44.82	Bonnie Plants 19 oz. Celebrity Tomato Vegetable Plant 0219 - The Home Depot
Lettuce Sprouts (HD)	3	$9.03	$27.09	Lettuce Premium Blend (15 ft. Seed Tape)
Lettuce Sprouts (WNC)	6	$2.50	$15.00	Product Page | WNC Urban Farms
Fountain Pump	2	$34.00	$68.00	TOTALPOND 140 GPH Fountain Pump 52217 - The Home Depot
Tubing	1	$24.77	$24.77	UDP 1/2 in. x 10 ft. Rubber Heater Hose T62006001 - The Home Depot
2x4 Lumber	2	$5.74	$11.48	2 in. x 4 in. x 10

				ft. Lumber D204SEC.294.10 - The Home Depot
Liquid pH Sensor	1	$33.99	$33.99	Amazon.com: Liquid PH 0-14 Value Sensor Module Accuracy 0.1pH + BNC Connect Terminal PH Electrode Probe Kit, PH Detection detect Sensor Module for Arduino
Circular Bin	1	$9.98	$9.98	HDX 21 Gal. Utility Tub Storage Tote with Rope Handles 2023-0560 - The Home Depot
Rectangular Bin	1	$9.98	$9.98	HDX 27 Gal. Tough Storage Tote in Black and Yellow 999-27G-HDX - The Home Depot
Total			$282.86	