

Food Waste to Hydroponic Nutrients via Anaerobic Digestion: a Student Scholar Model for Research Engagement

Dr. Jeremy C. Ferrell, Appalachian State University

Dr. Jeremy Ferrell is an Associate Professor in the Department of Sustainable Technology and the Built Environment where he teaches courses in renewable energy and conducts a research agenda around biomass energy systems, industrial ecology, and appropriate technology.

Jackson Hager, Appalachian State University

Food Waste to Hydroponic Nutrients via Anaerobic Digestion: a Student Scholar Model for Research Engagement

Jeremy Ferrell, PhD and Jackson Hager, MS

Appalachian State University

Abstract

Incorporating anaerobic digester (AD) effluent into hydroponic systems presents a promising approach for recycling nutrients from organic waste streams such as food waste. However, successful implementation requires characterization of the digestate's nutrient composition, appropriate dilution to prevent toxicity and imbalance, and pH adjustment. This study was conducted in two Controlled Environment Agriculture senior level courses (Fall 24 and Fall 25) in Appalachian State University's Department of Sustainable Technology & the Built Environment, where students were split into teams to conduct a plant growth experiment, analyze results, and compile a research paper collaboratively. The pedagogical goal is to develop a semester-long class project that encourages experiential learning and a student scholar model of active participation in research.

Romaine lettuce (*Lactuca sativa* var. *longifolia*) was selected for its short growth cycle (≈ 60 days), cold tolerance, and suitability for hydroponic cultivation. Treatment 1 (control) used a commercial fertilizer at a "mild vegetative growth" concentration; Treatment 2 (nutrient limited) used a 5% dilution of the control; and Treatment 3 used AD effluent from food waste, added at 12% by volume to achieve similar electrical conductivity as the control. Electrical conductivity, pH, and temperature were monitored throughout the seven-week growing period. At harvest, plants were analyzed for fresh leafy biomass, root biomass, and tissue analysis, with growth visually documented through a photo log. Results showed that the control treatment produced 2.3 times the leafy biomass of the 5% dilution and 2.8 times that of the AD effluent. Root to shoot ratio was highest in the 5% solution, suggesting greater root allocation under nutrient-limited conditions.

The educational goal was for students to take leadership roles in a class project that instills closed-loop thinking, design, experimentation, and teamwork to connect key societal issues (organic waste management) and decentralized food production (hydroponics). A survey designed to assess student learning outcomes was sent to all 32 participants. Responses were recorded using a Likert (1-5) as well as free response. Survey results showed 4.8 (increased understanding of technical system components), 4.7 (increased my confidence in participating in a research team), and 4.5 (increased my confidence in data analysis and interpretation). The ability to conduct the grow experiment during the semester (from seed to harvest in 2 months), results with clear visual differences, unexpected results, peer to peer learning, and hands-on nature were all cited as positive factors for deep learning. This paper details the experiment, results, student learning outcomes, and recommendations for future work.

Introduction

Students as Scholars

Preparing students to tackle the “wicked” problems of the 21st century such as climate change, food security and water scarcity, require new and creative approaches from educators. The top-down lecture style of content-delivery is no longer a suitable nor appropriate model for this next generation of engineers, scientists, and technologists. Engaging students in solutions-oriented practical applications to complex challenges can help channel focus and improve morale, remembering that nearly half of young people globally experience climate anxiety that affects their daily functioning [1]. The outcome of hands-on experiential learning include: improved academic performance, greater motivation, better problem-solving skills, and deeper comprehension of ideas [2]. The student scholar model where students are active participants in research and knowledge creation facilitate active inquiry or “learn by doing” and helps develop critical thinking, communication, technical skills, and reduces the teacher-student hierarchy as both parties become co-learners [3]. This model is also effect in integrating soft skills: teamwork, collaboration, coordination, and leadership development. While this type of project-based learning is demanding, requiring additional prep time, materials, dedicated space; it can be rewarding, meaningful and help create the scaffolding for life-long learners.

Problem Statement

Unpredictable weather, increased pest pressure, degradation of soil, and a changing climate have increased the challenge for traditional soil-based agriculture to feed a growing population. Land degradation is currently estimated to affect 23.5 percent of global land area” [4]. We are actively losing land that can be cultivated. Controlled environment agriculture (CEA) and hydroponics systems, typically in greenhouses, can help mitigate these issues by providing stabilized environments without the need for soil. Compared with soil-based systems, higher yields (more than 134%) and higher water conservation (> 50%) are commonly observed in hydroponics, allowing for more production per unit area [5].

In addition to loss of arable land, we confront an equally significant food waste issue. The USDA estimates that between 30-40% of the food supply becomes waste. This corresponds to 133 billion pounds and \$161 billion worth of food waste annually [6]. Negative societal impacts include the energetic costs of food waste’s life cycle, methane emissions in disposal and associated climate impacts, and a “toilet” mindset of discard where “flush and forget” is normalized in the face of excess consumption and a simultaneous alarming rise of food insecurity, 13% of U.S. households in 2023 [7]. The EPA states that 24% of municipal solid waste is food waste, which is responsible for 58% of the methane released from these landfills [8].

AD Effluent as a Resource & Challenges

This organic waste can be converted to fertilizer and renewable energy through anaerobic digestion (AD), whereby bacteria break down organic matter via four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The resultant products are biogas (methane and CO₂), as well as nutrient rich digestate. This digestate consists of two parts, liquid and solid. The liquid effluent contains essential plant macronutrients and micronutrients making it a valuable resource for agriculture. The solid digestate sludge also contains valuable nutrients and is typically composted aerobically for use as a soil amendment. As the digestion process mainly removes carbon from these organic wastes, the residual digestate contains high concentration of ammonia nitrogen, phosphorous, magnesium, calcium potassium,

and sulfur. Macronutrient concentrations in food-waste effluent have been reported in the following ranges, indicating its fertilizer potential: Total Nitrogen: 14-830mg/L, Total Phosphorous: 9-300mg/L, and Potassium: 25-36mg/L [9]. The wide nutrient range is directly related the inherent variable nature of foodwaste, especially in the protein content that determines total nitrogen.

While using AD effluent as a hydroponic nutrient represents a novel closed-loop solution, it is not without technical challenges. The pH range for most hydroponic vegetables is 5.5 to 6.5, however AD effluent exposed to air is typically between 7.5-8.5. This is due to the dissociation of carbonic acid and CO₂ stripping as CO₂ in the atmosphere has a lower partial pressure as compared to the effluent [10]. This results in a steady pH rise which also shifts the ammonia-ammonium equilibrium towards the production of free ammonia gas that can also be stripped into the air. This can result in ammonium toxicity and the burning plant's roots when absorbed. Hydroponic systems contain far fewer nitrifying bacteria as compared to soil, meaning less opportunity for conversion to plant available nitrate and ammonium [11]. Additionally, there are biological safety issues around AD effluent. While the AD process has been shown to significantly deactivate foodborne pathogens such as fecal coliforms, E. coli and salmonella, this is dependent on the AD substrate, loading rate, retention time, and the temperature and pH in the digester [12]. The USDA's National Organic Standards Board requires anaerobic digestion products to be processed via aerobic composting to reduce pathogens in order to be used in organic production [13]. This study used a Homebiogas 2.0 digester to convert food waste to biogas and effluent. Homebiogas, a company that manufactures and promotes small-scale digesters around the world, includes an effluent assay in the instruction manual, stating food waste effluent is less than 10cfu/100mL for E. Coli and fecal coliforms (less than 10 colony-forming units is practically undetectable in laboratory numbers) [14]. Finally, excess nutrients present in the effluent can result in eutrophication, leading to algae blooms and dead zones leaving less oxygen available for plants. [15]. For these reasons, effluent characterization, treatment, dilution, and safety issues must be considered for use as a hydroponic nutrient source.

Purpose of Study

By further researching hydroponic nutrient solutions, we are hopeful that more circular practices will be used by incorporating anaerobic digestion to process agricultural and food wastes. By this method, it will also be possible to use the biogas from the AD process for heating or other energetic needs, and the liquid effluent as fertilizer in food production systems such as hydroponics. The goal of this study is to expand the knowledge of how effective an AD effluent hydroponic solution, sourced from a solely vegetative food waste anaerobic digester, compares to a commercial hydroponic solution.

Methods

In this study students evaluated the performance of AD effluent as a hydroponic nutrient solution by comparing three treatments: a standard mild vegetative commercial hydroponic solution (control), a 5% diluted version of the same commercial solution, and a vegetative food waste-only AD effluent solution diluted with water. Romaine lettuce was used as the test crop due to hydroponic adaptability, cold tolerance, and its short development, from seed to harvest in 60 days.

Student Participation

Students were engaged in every aspect of this project from seed starting the first week of the semester to transplant to the hydroponic system to final harvest. To complete the research paper, students were divided into 5 groups: 1) Intro, Literature Review, Methods, 2) Data Analysis & Visualization (growing conditions), 3) Data Analysis & Visualization (harvest metrics), 4) Data Analysis & Visualization-analysis from 3rd party labs, and 5) Plant Growth Photo Log. Two students served as editors to synthesize all group outputs into a cohesive well-formatted document. The entire class participated in regular group updates, as well as the discussion/conclusion section, and recommendations for future work. The writing was entirely collaborative, using a shared class drive, culminating in a final report in the style of a research paper.

Hydroponic System Setup

Seeds were started in fertilizer-free propagation mix and grown in a greenhouse for the first 30 days. Seedlings were transplanted in plastic net cones filled with expanded clay aggregate to support root development while allowing full root submersion. Three identical 100 L plastic hydroponic totes were prepared, each with evenly spaced openings in the lid to support plant cones. Twelve romaine lettuce seedlings were placed into each tote to ensure consistent spacing and comparable growing conditions across treatments. Each tote was filled with approximately 85 L of solution and continuously aerated using aquarium air pumps and air stones to prevent anaerobic root conditions.

The nutrient solutions were prepared as follows: Mild vegetative control: 112 mL each of General Hydroponics FloraGro, FloraMicro, and FloraBloom mixed with 85 L of water. 5% mild vegetative solution: 5.6 mL each of FloraGro, FloraMicro, and FloraBloom mixed with 85 L of water. AD effluent solution: 12 L of anaerobic digester effluent mixed with 73 L of water to match the EC (electrical conductivity) of the control. The effluent was produced from a HomeBiogas anaerobic digester fed solely with vegetative food waste located at the App State Nexus Research Facility.

Monitoring and Environmental Control

Each hydroponic tote was equipped with a Bluelab Guardian monitor to measure pH, electrical conductivity (EC), and temperature (°F). Sensor probes were submerged directly in each solution. Manual readings were recorded every 1–3 days to supplement logged data and verify sensor accuracy. During the first two weeks of the experiment, phosphoric acid (pH down) was added as needed to the AD effluent solution to adjust pH to a target range of 6.0–6.5. No additional nutrients were added after initial solution preparation.

Nutrient and Solution Analysis

Before dilution, a sample of the raw AD effluent was collected and sent to the North Carolina Department of Agriculture and Consumer Services for full nutrient characterization. Approximately two-thirds of the way through the experiment, samples from all three hydroponic solutions were collected and analyzed by the same laboratory to determine macro- and micronutrient concentrations, EC, alkalinity, and pH. The nutritional breakdown of these three solutions can be seen in Table 1.

Table 1 Pre-harvest hydroponic solution analysis (from NCDA & CS).

Nutrient Name	Mild Veg.	5% Mild Veg.	AD Effluent
Inorganic Nitrogen (mg/L)	142.00	4.70	136.00
Ammonium (mg/L)	19.90	0.68	120.00
Nitrate (mg/L)	122.00	4.03	16.00
Phosphorus (mg/L)	58.00	12.70	285.00
Potassium (mg/L)	151.00	3.46	106.00
Calcium (mg/L)	119.00	17.40	25.70
Magnesium (mg/L)	37.10	3.50	10.70
Sulfur (mg/L)	64.10	10.50	10.10
Iron (mg/L)	1.90	0.05	0.04
Manganese (mg/L)	0.27	0.00	0.01
Zinc (mg/L)	0.33	0.02	0.01
Copper (mg/L)	0.16	0.01	0.01
Boron (mg/L)	0.34	0.02	0.10
Aluminum (mg/L)	0.00	0.00	0.01
Sodium (mg/L)	20.20	18.50	36.40
Chloride (mg/L)	20.20	17.90	57.50
Soluble Salts 10^{-5} S/cm	163.00	23.00	153.00
EC mS/cm	1.63	0.23	1.53
pH	5.91	6.63	6.48
Bicarbonate	0.28	0.27	2.68
Total Alkalinity (ppm CaCO_3)	14.00	13.50	134.00
Acid Requirement (oz/100 gal)	0.00	0.00	0.95
Hardness (ppm CaCO_3)	450.00	57.80	108.00
SAR	0.41	1.06	1.52

Plant Data Collection

Throughout the growth period, visual observations and photographs were taken to document plant health, coloration, and growth differences. At harvest, the following measurements were collected and averaged for each treatment: leaf length (cm), root length (cm), fresh shoot biomass (g), and fresh root biomass (g).

Plant Tissue Analysis

After harvest, lettuce leaves from each treatment were dried and submitted to the North Carolina Department of Agriculture and Consumer Services for plant tissue analysis. Macronutrient and micronutrient concentrations were measured to assess nutrient uptake differences among treatments.

Data Analysis

All quantitative data were compiled in for statical analysis and to compare treatments for biomass, root-to-shoot ratios, nutrient concentrations, pH, and EC trends. Results were interpreted in relation to nutrient availability, solution chemistry, and observed plant health.

Results

Overall Plant Growth

At harvest, marketable lettuce leaves as determined by leaf color and absence of imperfections, were weighed for each sample, 12 samples per treatment. Lettuce grown in the mild vegetative control solution exhibited the greatest overall growth, 2.3 times the yield of the 5% mild vegetative solution and 2.8 times the yield of the AD effluent solution. These visual comparisons, shown below in Figure 3, illustrate the progressive reduction in plant size across the respective treatments from the beginning to the end of the experiment. Leaf length, root biomass, and root length were also recorded.

Table 2. Plant harvest characteristics by treatment

Treatment	n	Leaf Biomass (g)		Leaf Length (cm)		Root Biomass (g)		Root Length (cm)		Root/Shoot Ratio	
		Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Control (Mild Veg Grow)	12	64.58	16.08	24.46	2.52	7.17	2.07	39.98	10.91	0.1155	0.0370
5% of Mild Veg	12	28.17	8.45	18.71	1.66	6.58	1.26	43.98	12.58	0.2439	0.0487
AD Effluent	12	23.42	5.04	17.13	1.68	4.92	0.86	19.00	6.29	0.2151	0.0342

A two sample T-test assuming unequal variances was conducted between the Control and AD treatments resulting in a p value of < 0.0001 , $\alpha = 0.05$, demonstrating a statistical difference between these groups despite a large variance in the control group (see Appendix 1).

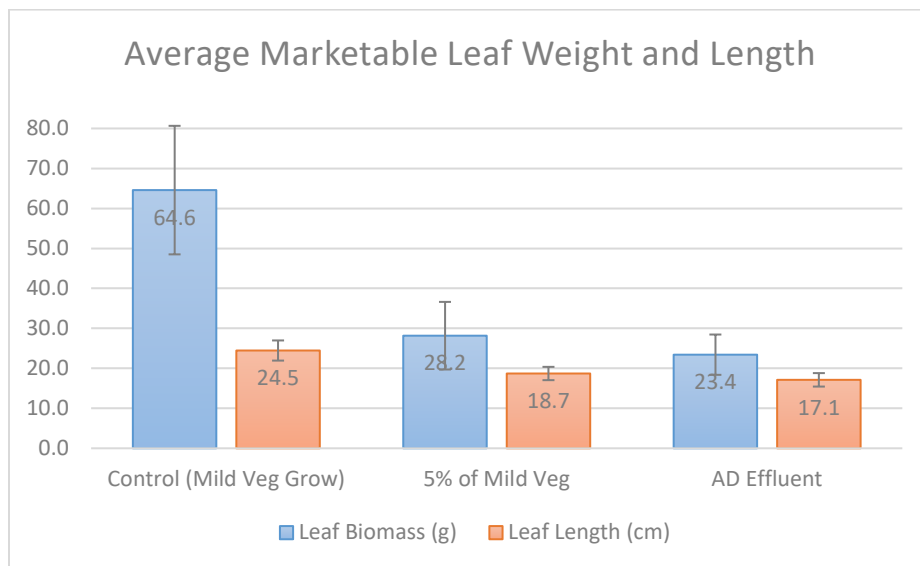


Figure 1. Harvest leaf data with standard deviations.



Figure 2 (Left). Romaine seedlings in soil prior to hydroponic transplant. Figure 3 (Right). Final image of lettuce before harvest (Control on the left, 5% Mild Veg in the Middle, AD Effluent on the right)

Root to Shoot Measurements

Post-harvest measurements indicated that plants grown in the control solution produced the greatest average leaf length and leaf biomass as well as root biomass. The 5% treatment showed the highest root-shoot ratio, indicating a greater proportional investment in root growth relative to shoot biomass in this nutrient scarce treatment. Plants grown in the AD effluent solution produced the shortest roots and leaves, though dark green, as well as the lowest total biomass.

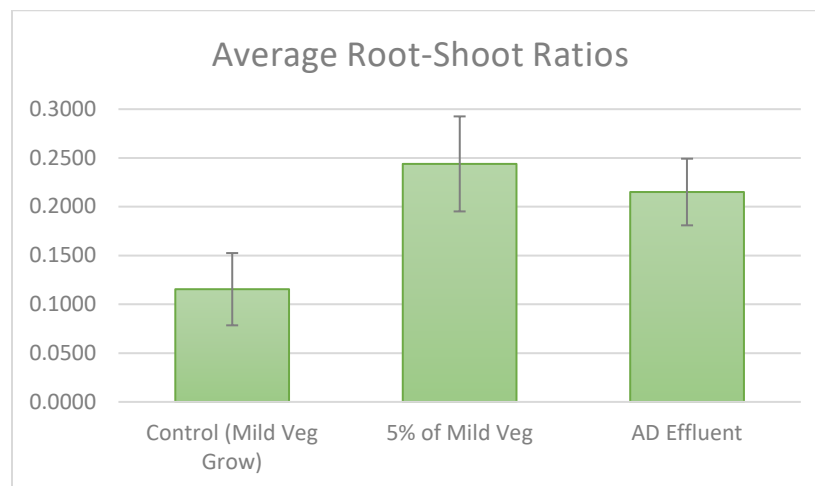


Figure 4. Root (g) to Shoot (g) ratios with standard deviations.

Nutrient Composition of Solutions

Laboratory analysis revealed distinct differences in nutrient composition among the three hydroponic solutions. The AD effluent solution contained elevated ammonium and phosphorus concentrations compared to both commercial solutions, while nitrate, calcium, magnesium, and several micronutrients were lower than those in the mild vegetative control.

The AD effluent solution exhibited higher phosphorus concentrations than both the mild vegetative solution and the 5% mild vegetative solution (Figure 5). In contrast, the 5% mild vegetative solution contained minimal concentrations of nitrogen, phosphorus, and potassium (NPK). Nitrogen and potassium levels in the AD effluent and mild vegetative solutions were similar, however the nitrogen was

in different forms. Figure 6 depicts elevated levels of ammonium in the AD effluent. Literature suggests that ammonium concentrations of over 50 mg/L can cause toxicity, lead to pH drops and imbalance, and reduce plant growth [16].

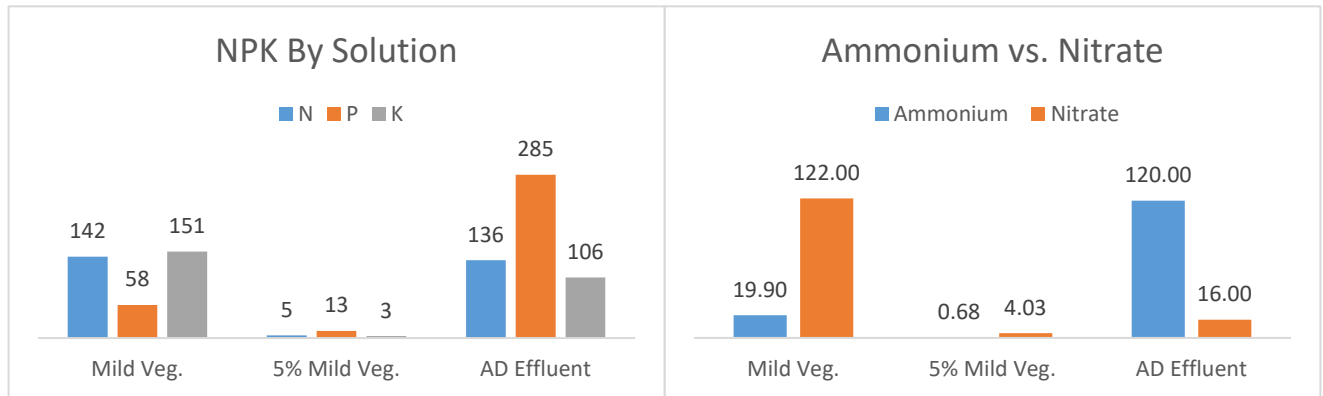


Figure 5. Nitrogen, Phosphorus, and Potassium (NPK) Concentrations per Treatment. Figure 6. Nitrate and Ammonium Concentration between Treatments.

pH and Electrical Conductivity Trends

The pH measurements in Figure 7 showed that the AD effluent solution initially exhibited higher alkalinity before stabilizing near pH 6.5 following adjustment during the early stages of the experiment. The 5% mild vegetative solution remained stable throughout the growth period, while the mild vegetative control experienced a decrease in pH during the final weeks of growth. Average EC values remained stable over time for both the control and AD effluent treatments, whereas EC remained consistently low for the 5% mild vegetative solution.



Figure 7. pH of treatments over time (left). Figure 8. Electrical Conductivity over time.

Plant Tissue Analysis

The plant tissue analysis, presented in Tables 2 and 3, revealed clear differences in nutrient composition among the treatments. Lettuce grown in the mild vegetative solution exhibited the highest total nitrate concentration (6,280 mg/kg), followed by the AD effluent (1,270 mg/kg) and the 5% mild vegetative treatment (25.9 mg/kg). Potassium concentrations followed the same pattern, with values of 6.74% mg/kg, 5.64% mg/kg, and 1.22% mg/kg, respectively.

Table 3. Analysis of Key Macronutrients of Leaves per Solution from the Plant Tissue Analysis (Nutrient measurements are given in units of mg/kg, unless otherwise specified).

Nutrient Name	Mild Veg.	5% Mild Veg.	AD Effluent
Nitrogen	3.45%	1.32%	4.40%
Nitrate	6280	25.9	1270
Phosphorus	0.56%	0.28%	0.60%
Potassium	6.74%	1.22%	5.64%
Calcium	0.63%	0.56%	0.61%
Magnesium	0.19%	0.26%	0.19%
Sulfur	0.23%	0.09%	0.27%

Table 4. Analysis of Key Micronutrients of Leaves per Solution from the Plant Tissue Analysis. (Nutrient measurements are given in units of mg/kg, unless otherwise specified).

Nutrient Name	Mild Veg.	5% Mild Veg.	AD Effluent
Iron	150	52.1	86.0
Manganese	74.2	26.3	41.7
Zinc	23.9	12.1	31.7
Copper	6.69	3.35	2.50
Boron	21.0	12.8	22.1
Aluminum	9.54	15.5	21.7
Sodium	0.07	0.68	0.18

Phosphorus concentrations were greater in the AD effluent treatment (0.60% mg/kg) than in the 5% mild vegetative solution (0.28% mg/kg), and the control (0.56% mg/kg). In contrast, calcium concentrations were reduced in both the AD effluent and 5% mild vegetative treatments relative to the control. Micronutrient uptake varied by solution, but the control showed greater uptake followed by the AD effluent solution, then the 5% mild.

Analysis of Learning Objectives

The educational goal was to develop a semester long research project that instills closed-loop thinking, design, experimentation, and teamwork to connect key societal issues (organic waste management) and advanced decentralized food production (hydroponics). This class project addressed all three of the curricula goals of students in Department of Sustainable Technology and the Built Environment: 1) *develop fundamental proficiencies*, 2) *apply techniques, skills, and tools necessary to implement renewable energy and sustainable technology systems*, and 3) *develop professional skills necessary for success in the discipline*.

A survey designed to assess student learning outcomes was sent to all 32 participants. Responses were recorded using a Likert (1-5), shown in Table 4. Free Responses to prompts (technical skills, unexpected results, and next steps) are shown in Tables 5-7. The responses to “next steps” for future research or experimental iterations show positive learning outcomes that display synthesis of fundamentals, critical thinking, and internalizing the entire project including its limitations.

Table 5. Survey Results from student participants (Likert Scale 1-5)

Question:	Average Score
1) This project increased my understanding of hydroponic systems and the use of AD effluent as an alternative nutrient solution.	4.8
2) This project increased my confidence in participating in research teams that work towards a common goal.	4.7
3) This project increased my understanding in data analysis and interpretation.	4.5

Table 6. Selected Free Responses to “Which technical skills (e.g., problem-solving, teamwork, instrumentation, data interpretation) did you develop most through this project?”

<i>I learned how to pick out and discern the most relevant information in data collection.</i>
<i>I gained insight on hydroponic growing and how it can be utilized for appropriate plants in a controlled environment.</i>
<i>increased my skills in logging and manipulating data to create visuals</i>
<i>We learned to work together in a team and provide research and feedback to each other to make a collaborative piece.</i>
<i>I learned how to properly edit and format research papers. I was able to work on my teamwork skills by creating resources for my peers to easily use and be accessible.</i>
<i>One of the skills that I developed the most throughout this project was the process of experimentation, and all the steps it takes to prepare for a project of this degree.</i>

Table 7. Free Responses to, "What was the most surprising or unexpected result of the experiment?"

<i>The AD effluent produced such poorly developed lettuce in comparison to the synthetic fertilizer.</i>
<i>How similar the results were for the 5% mild vegetative and mild vegetative (control) solutions.</i>
<i>I was really surprised by the nutrient concentration of the Anaerobic Digester. It was also interesting to see that the amount of nutrients doesn't matter if the nutrients aren't in an available form.</i>
<i>Seeing the actual impact of the data in pictures.</i>
<i>The pH imbalances of the AD effluent and the falling pH of the control which still produced high quality lettuce.</i>

Table 8. Free Responses to " what would be your next research question or design (physical or experimental) improvement?"

<i>How does the AD effluent affect growth in a soil culture? Could some bacterial colony in the hydroponic solution affect nutrient uptake in the organic fertilizer?</i>
<i>I would like to research adding microbes into the digestate solution to try and improve nitrogen availability.</i>
<i>I would look further into the reasoning behind pH fluctuations in the AD effluent solution</i>
<i>Control the material that enters the digester so the AD effluent can be manipulated to a better fertilizer for lettuce?</i>
<i>I would like to further study how we could make effluent more useful through pretreatments.</i>

Discussion and Recommendations for Future Research

The results of this study demonstrate that anaerobic digester (AD) effluent, when diluted and used as a hydroponic nutrient solution, does not support romaine lettuce growth as well as a standard commercial hydroponic solution. Plants grown in the control produced greater leaf biomass, leaf length, and overall better marketable produce, suggesting that the balanced nutrient profile of the commercial solution more effectively met plants' growing needs.

Although plant growth in the AD effluent treatment was reduced, the tissue and solution analysis revealed elevated phosphorus and a normal range of nitrogen and potassium concentrations, confirming that nutrients from digested food waste are plant available. However, tissue deficiencies in several micronutrients, along with the high concentration of ammonium are likely the main issues, contributing to reduced biomass and shorter root systems observed in the effluent treatment.

The 5% mild vegetative solution produced limited shoot growth but comparatively greater root development, as reflected by higher root-to-shoot ratios. This is expected with nutrient-limited conditions, where plants allocate resources toward root growth to increase nutrient uptake. The 5% mild vegetative tissue analysis reveals lower concentrations of all nutrients, especially nitrogen, meaning its biomass is less nutritional per unit mass. Together, these results suggest that while AD effluent contains valuable nutrients, it requires further treatment or supplementation to function effectively as a standalone hydroponic solution.

Future research should investigate methods to optimize anaerobic digester effluent for hydroponic use, including more controlled feedstock inputs, developing an aquaculture-style biofilter for nitrification, and pre-treatment strategies such as the use of biochar to absorb ammonium [17]. Evaluating different dilution ratios and blending AD effluent with commercial hydroponic nutrients may help identify methods that improve plant performance while maintaining sustainability benefits.

Additional studies should also assess the performance of AD effluent across multiple crop types and growth cycles to improve reliability and generalizability. Increasing replication and incorporating statistical analyses would further strengthen conclusions and support the broader application of this approach in sustainable food production systems.

Conclusion

This study evaluated the feasibility of using food-waste derived anaerobic digester effluent as a hydroponic nutrient solution for romaine lettuce production. While the effluent contained recoverable nutrients, plant growth and biomass were consistently lower than those achieved using a standard commercial hydroponic solution. This could be attributed to an imbalance of nutrients, such as excessive ammonia concentration with insufficient amounts of nitrate. This result could also have been caused by the lower concentrations of micronutrients, such as iron, manganese, and copper, compared to those of the control. This imbalance of nutrients could have led to the stunted growth of the crops grown in the AD effluent solution, in comparison to the control. However, without further repetition of this growth experiment, it remains difficult to identify which of these imbalances could have caused this outcome.

Despite these limitations, the results demonstrate that anaerobic digestion of vegetative food waste can produce a nutrient-rich effluent with potential agricultural use. With further optimization, AD effluent could contribute to a more sustainable, circular food production system by reducing food waste and reliance on synthetic fertilizers. This simple research design provides a foundation for future studies aimed at improving nutrient recovery and integration of waste management technologies.

These types of semester-long team research projects for senior-level technology students can be rewarding and provide multiple pathways for achieving learning outcomes. The ability to conduct the grow experiment during the semester (from seed to harvest in 2 months), resulting in clear visual differences, unexpected results, peer-to-peer learning, and a hands-on nature were all cited as positive factors for deep learning.

Acknowledgements

This work was made possible by the hard work of the Fall 2025 Greenhouse and CEA course for conducting the experiment and creating the technical results presented here.

Editors: Lisabella Cataldi, David Bass. Intro & Methods: Gabriel Seeger, Kye Harris. Data Analysis Visualization (Growing conditions): Rigo Garcia Martinez, Dylan James, Grace Wegner. Data Analysis Visualization (Harvest metrics): Cole Thompson, Blayne Del Priore, Josh Willoughby. Data Analysis Visualization (AD Effluent Analysis): Otto Smith, Evan Guiney, John-Henry Barwick. Plant Growth Photo Log: Kinsey Bolick, Ethan Porter.

The App State Nexus research facility also receives support from the Department of Sustainable Technology and Built Environment and the Research Institute of Energy, Environment, and Economics.

References

- [1] Hickman C, Marks E, Pihkala P et al. 2021. Climate anxiety in children and young people and their beliefs about government responses to climate change: a global survey. *The Lancet Planetary Health*, 5, e863-e873
- [2] Shivaramu, H.T., Aveen, K.P. & Ullal, V.N. 2025. The role of experiential learning in improving academic performance and student satisfaction in engineering education. *Discov Educ* 4, 545 (2025). <https://doi.org/10.1007/s44217-025-01019-y>
- [3] O'Connell, M. T., Adawi, T., Wallin, P., & Stöhr, C. (2026). Engineering students and professionals as co-learners: epistemic practices and positioning. *European Journal of Engineering Education*, 51(2), 460–478. <https://doi.org/10.1080/03043797.2025.2566697>
- [4] Bai, Z. G., Dent, D. L., Olsson, L. and Schaepman, M. E. (2008) 'ProxyGlobal Assessment of Land Degradation', *Soil Use & Management*, 24, pp. 223–234. [Proxy global assessment of land degradation - Bai - 2008 - Soil Use and Management - Wiley Online Library](#)
- [5] Wang, L., Ning, S., Zheng, W., Guo, J., Li, Y., Li, Y., Chen, X., Ben-Gal, A., & Wei, X. (2025, November 20). *Performance analysis of two typical greenhouse lettuce production systems: Commercial hydroponic production and traditional soil cultivation*. *Frontiers*. <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1165856/full>
- [6] USDA. (n.d.). *Food Waste Faqs*. Food Waste FAQs. <https://www.usda.gov/about-food/food-safety/food-loss-and-waste/food-waste-faqs>
- [7] USDA Economic Research Service. Food Security in the U.S. – Key Statistics and Graphics. <https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us/key-statistics->

[graphics#:~:text=Food%20insecure%E2%80%9494At%20times%20during,\(10.2%20million\)%20in%202022.](#)

[8] Environmental Protection Agency. (2025, March 20). Quantifying Methane Emissions from Landfilled Food Waste. EPA. <https://www.epa.gov/land-research/quantifying-methane-emissions-landfilled-food-waste>

[9] Lehto, J., Järvelä, E. (2025). Valorisation of anaerobic digestate to nutrients and humic substances, Waste Management, Volume 192, 2025, Pages 39-46, ISSN 0956-053X, <https://doi.org/10.1016/j.wasman.2024.11.033>

[10] Cohen, Y., Kirchmann, H. (2004). Increasing the pH of Wastewater to High Levels with Difference Gases-CO₂ Stripping. Water Air and Soil Pollution 159 (1): 265-275. DOI: [10.1023/B:WATE.0000049185.69759.b0](https://doi.org/10.1023/B:WATE.0000049185.69759.b0)

[11] Neal, J. (2014). *UFL*. Anaerobic Digester Effluent as Fertilizer for Hydroponically Grown Tomatoes. <https://ufdcimages.uflib.ufl.edu/UF/00/09/15/23/00710/Neal,%20Jaquelyn%20Final.pdf>

[12] Ma, G., Chen, Y., Ndegwa, N. (2022). Anaerobic digestion process deactivates major pathogens in biowaste: A meta-analysis, Renewable and Sustainable Energy Reviews, Volume 153, 2022, 111752, ISSN 1364-0321, <https://doi.org/10.1016/j.rser.2021.111752>.

[13] USDA. (2017). National Organic Standards Board. Petition to amend 205.203(c) to include anaerobic digestion products. Retrieved from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/<https://www.ams.usda.gov/sites/default/files/media/CSAnaerobicDigestateFinalRec.pdf>

[14] Homebiogas. (2022). HBG 7.0 Household Biogas System Owner's Manual. Version 140822. Retrieved from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://marketing-portal.homebiogas.com/wp-content/uploads/HBG7_0822_YellowGasPipe.pdf

[15] Mustak, M.B., Iman, Y.E., Abrar, M.F. et al. Evaluation of the suitability of reusing treated greywater for hydroponic lettuce cultivation: chemical health risk analysis. Environ Dev Sustain 27, 18077–18104 (2025). <https://doi.org/10.1007/s10668-024-04696-1>

[16] Xu, J., Che, G., et. al. (2025). Optimizing nitrogen form ratio for enhanced nutrient uptake and lettuce performance in hydroponic systems. Bioresource Technology Reports, Volume 32, 2025, 102384. <https://doi.org/10.1016/j.biteb.2025.102384>.

[17] Cai, Y., Zhu, M., et al. (2022). The role of biochar on alleviating ammonia toxicity in anaerobic digestion of nitrogen-rich wastes: A review, Bioresource Technology, Volume 351, 2022, 126924, <https://doi.org/10.1016/j.biortech.2022.126924>.

Appendix

Appendix 1-

Leafy Biomass for each treatment:

Leafy Biomass (g)			
Plant ID	Control	5%	AD Eff.
1	50	18	26
2	92	34	11
3	59	50	18
4	65	24	25
5	61	26	22
6	72	20	25
7	78	26	33
8	66	30	25
9	63	34	23
10	32	27	23
11	49	31	27
12	88	18	23

t-Test: Two-Sample Assuming Unequal Variances

	<i>Control</i>	<i>AD Eff.</i>
Mean	64.58333	23.41667
Variance	281.9015	27.7197
Observations	12	12
Hypothesized Mean Difference	0	
df	13	
t Stat	8.104402	
P(T<=t) one-tail	9.7E-07	
t Critical one-tail	1.770933	
P(T<=t) two-tail	1.94E-06	
t Critical two-tail	2.160369	

Appendix 2:

Plant Growth Photo Log

This photo log was created to visually show the changes in plant growth over time. Key dates are highlighted such as 5 days after planting, Day of transplanting and harvesting. Photos included in this were chosen at 10-day intervals. Across the photo log, the Mild Veg plants show darker leaves and larger biomass by day 20, while the AD effluent plants show chlorosis and slower structural development.

8.25.25

- Romaine
- Photos taken 5 days after planting.
- 2-3 seeds per cell



9.13.25

Growth Solution: Mild Veg

- Slight yellowing
- Only difference is growth solution (first day in hydroponic system)
- Plants will remain droopy until they adjust to their new growing environment and grow stronger roots.
- Roots will grow into the clay aggregate used to provide support and structure for the plants.



9.13.25

Growth Solution: 5% Mild Veg

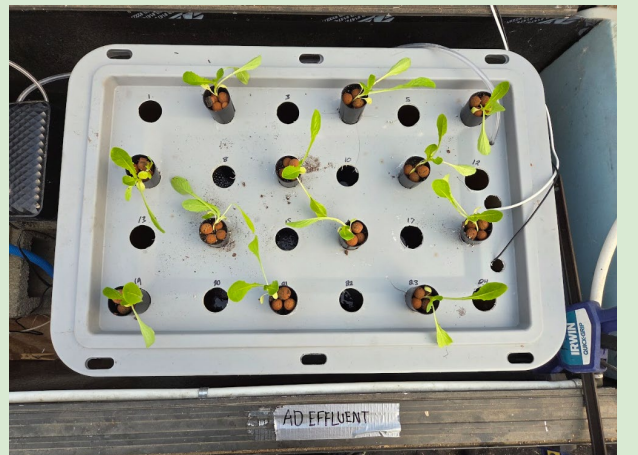
- Slight yellowing
- Only difference is growth solution (first day in hydroponic system)
- Plants will remain droopy until they adjust to their new growing environment and grow stronger roots.
- Roots will grow into the clay aggregate used to provide support and structure for the plants.



9.13.25

Growth Solution: Effluent

- Slight yellowing
- Only difference is growth solution (first day in hydroponic system)
- Plants will remain droopy until they adjust to their new growing environment and grow stronger roots.
- Roots will grow into the clay aggregate used to provide support and structure for the plants.



9.23.25

Growth Solution: Mild Veg

- Noticeable presence of white flies
- Slight yellowing (potentially due to the white flies)
- Inconsistent individual plant sizes
- Plants have begun to strengthen and stand up.

9.23.25

Growth Solution: 5% Mild Veg

- Noticeable presence of white flies
- Plants have begun to strengthen and stand up.

9.23.25

Growth Solution: AD Effluent

- Noticeable presence of white flies
- Plants have begun to strengthen and stand up.
- Leaves are lighter in color when compared to the other two solutions.
- Based on the CI levels for the AD Effluent being the highest out of the other two solutions, it is assumed that this factor could be partially responsible for the yellowing of the outer leaves.



10.2.25

Growth Solution: Mild Veg

- Inconsistent individual plant sizes
- Dark colored leaves

10.2.25

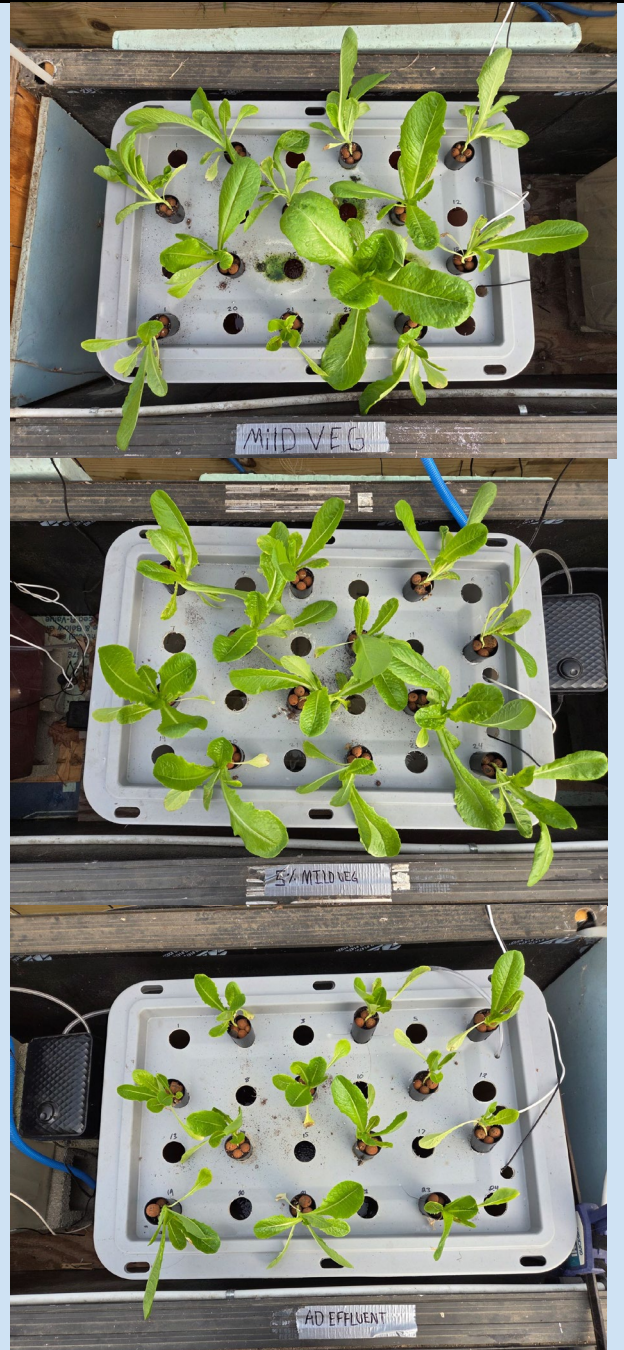
Growth Solution: 5% Mild Veg

- Consistent individual plant size
- Dark colored leaves
- Smallest leaves show slight yellowing.

10.2.25

Growth Solution: AD Effluent

- Consistent individual plant sizes
- Smallest average plant sizes
- Smallest leaves show yellowing



10.11.25

Growth Solution: Mild Veg

- Show the most growth, with the healthiest looking leaves
- Based on the data analysis, the mild veg concentration had the best NPK balance ratio, which is why their leaves are the darkest color, largest in size, and their root system is the most developed.
- This solution shows the most variation of micronutrients throughout the whole growing process, which could be the reason there are inconsistent plant sizes.



10.11.25

Growth Solution: 5% Mild Veg

- The 5% mild veg concentration had the least amount of micro & macronutrients, however, they had the most consistency when it comes to individual plant size due to the minimal variation of availability throughout the growing process.



10.11.25

Growth Solution: AD Effluent

- Shown the least amount of growth when compared to the other two solutions
- Has the most deficiencies caused by white flies
- Smaller leaves show browning
- Stunted growth due to the high ammonium concentration of the AD Effluent - leafy greens tend to be more sensitive to high ammonium concentrations



10.22.25

Growth Solution: Mild Veg

- Harvest day!
- One of the most prominent observations of the plants at this stage is the root networks, and how they began to grow together and combine root systems.



10.22.25

Growth Solution: Mild veg, 5% mild veg, AD Effluent (left to right)

- The photo represents a comparison between the three growing solutions on harvest day. As you can tell, the Mild Veg solution resulted in the fullest plants with the darkest color. Plants grown in this solution also showed the least amount of yellowing.



Appendix 3 – Project photos



Students transplanting seedlings into hydroponic system



Watering newly transplanted seedlings.



Our Home Biogas digester generated the effluent from food waste.



Students record biomass characteristics (weights and lengths) on harvest day.