INTRODUCTION

Throughout history, the industrial and sociopolitical needs of mankind have driven the evolution of chemical engineering research and its curriculum to best prepare students for their post-educational endeavors.[1,2] At the turn of the 20th century, the rise of the petroleum and chemical industries catalyzed the development of chemical engineering education at several universities to meet the demands of society .[1−4] The increasing demand of the ChE skillset from these industries steered much of the chemical engineering research and curriculum at universities to focus on petrochemical topics.[1−4] In the mid to late 20th century, the rise of the pharmaceutical and biotechnology industries increased the demand for ChE degrees to match manufacturing, research and development needs once again.[5,6] Many ChE curricula have evolved to include one or two bio-focused courses.[6]

Now in the 21st century, there are new emerging fields that apply to chemical engineers and may lead to further adjustments to topics and courses taught in the ChE curriculum.[1] One pressing area is sustainability, specifically to provide adequate life sustaining resources, including clean water, energy, and food, to the increasing human population.

Food, water, energy, and climate have an interconnected relationship which is known as the water-energy-food (WEF) nexus The WEF nexus identifies that disturbances to any one system will have a significant impact on not only the other primary systems but their numerous dependent subsystems. In 2022, the National Academy of Sciences (NAS) recognized in their "New Directions for Chemical Engineering", that chemical engineers will play a critical role in developing the solutions required to address this WEF nexus challenge. In their report, the NAS highlights that ChE education should again shift its focus and evolve to encourage the development of sustainable engineering solutions for environmental systems, such as hydroponic and aquaponic technologies, to address the WEF nexus challenge. As detailed by the NAS, the solution to the WEF nexus challenge is not simply to produce more of these resources, but rather to revolutionize the efficiency and sustainability of the systems in which society produces these resources from.[7]

Since the origin of the discipline, ChE has made vital contributions to the energy, pharmaceutical, chemical, and consumer products industries amongst several others.[7] Although the agricultural industry has long been considered part of other disciplines, the macro and microscopic level of systems thinking involved in ChE creates an opportunity for ChEs to innovate and address the WEF nexus challenges.[7] However, the current ChE curriculum at many universities does not require courses that cover many of the key topics needed to provide students with the background to make impacts in this area, such as biology and education for sustainable development (ESD) .[2,*] The large majority of the ChE curriculum continues to focus on petroleum refining, and chemical production industries. [2] Meanwhile, the biological concepts incorporated into the ChE curriculum has been limited to those pertaining to mammalian cells, bacteria, and viruses Shaffer and Lopez concluded that out of the 13 top ChE programs in the United States, only 8 of them require some type of Biology course In most ChE programs, the required course is typically biochemistry or molecular biology.[8] It is seen that ESD is not incorporated into chemical engineering curriculum as a requirement outside of being an elective which students can explore with their own interest.*

A large majority of the ChE curriculum also continues to exercise traditional lecture style teaching, which has been proven less effective in developing students' skills compared to hands-on learning techniques. These skills are especially important to not only maintain student attention but to also develop technical skills in a laboratory setting. Standard lecture setting courses deter creativity in addition to being detrimental to students' retention of material.[10] One opportunity to address the arising WEF nexus challenges in the ChE curriculum is by incorporating a hands-on hydroponic experiment that is more useful for solving the industrial problems of the present and future, and less on the various petrochemical topics that have been an integral part of the curriculum for decades.[11,12]Through the integration of hands on learning (HOL) in the ChE curriculum, students will not only become more excited to learn and have an expedited learning process but it will also alleviate the pressure from instructors to include more content throughout the course, allowing students to learn new topics. This paper presents a hands-on laboratory experiment that was piloted as part of Process Engineering Lab II can be used to expose ChE students to plant biology, horticulture, and sustainable environmental systems.

Laboratory Experiment Objectives

Process Engineering Lab II (PELII) is the continuation of a senior unit operation course. Over 60 percent of PELII focused on students designing an experiment for Process Engineering Lab and conducting experiments related to their idea. Students were divided into groups of 4 – 5 based on interests, and they were instructed to research a topic of interest, such as cosmetics, pharmaceuticals, energy, etc. Students were then tasked with serving as educational consultants to design a new hands-on senior chemical engineering lab experiment around their topic of interest that has some practical applications and could theoretically be integrated into PELII as soon as Spring 2024. Students had two weeks to come up their experiment and complete background research. Students were allowed to schedule consultation time with the professor and teaching assistants. In the fourth week of the semester, teams met with the professor to explain their experimental plan and to convince the professor that their experiment was rigorous enough and feasible to be completed in the semester. The design requirements were that the experiment should be:

- ✔ Open-ended - students should have the ability to select several variables to be altered.
- ✔ Cost-effective - the cost is less than $500 per semester.
- ✔ Safe - students should not be exposed to dangerous conditions or materials during experimentation.

- ✔ Quantitative - Students should be able to collect at least 12 data points, 4 conditions in triplicate, per 5-hour laboratory session.
- ✔ Original - Proposed experiments cannot be any experiment that was completed in any previous Process Engineering Lab or ChE course.

Once a group receives approval for their experiment, they spend five weeks in lab for a total of 25 hours conducting experiments. Each member is responsible for overseeing one variable of interest for the team. Outside of class, students are expected to analyze their data and complete weekly checkpoint assignments where teams write drafts of different sections of their lab report and provide analysis on their results. At the conclusion of the experiment every student delivered a seven-minute oral presentation that summarized the group's findings to the instructor and classmates.

As an educational tool, this laboratory experiment can provide ChE students with a practical understanding of plant biology principles and optimization of sustainable environmental systems. The experiment can also foster critical thinking, data analysis, and problem-solving skills as students analyze and interpret experimental results. Furthermore, this laboratory experiment inspires ChE students to explore interdisciplinary applications of their discipline in agriculture and horticulture, as well as developing a deeper understanding of the sustainability challenges and opportunities in modern agriculture.

Comparison of Hydroponics as an alternative to traditional agricultural practices

As global concerns regarding soil degradation, environmental pollution, climate change, and water scarcity increase, the development of sustainable environmental systems to minimize these issues within relevant industries is urgent and requires immediate action. According to the United Nations, 72% of annual water withdrawals are used in agriculture practices, and the agriculture industry will have to grow by more than 50% by 2050 to meet the substantially growing world population.[1,2] Irrigation techniques, although greatly improved, have an efficiency of 65%, with run-off water posing a health risk due to the toxic pesticides used. Soil-based farming is also an energy intensive process, and the energy used to cultivate crops, including the production of pesticides and fertilizers, produces a large amount of greenhouse gases.[3] Depending on the crop produced, carbon emissions could range anywhere from 150 – 350 kgC/ha per year.[4] A less water and energy intensive agricultural alternative will need to be integrated to meet the demand of a rapidly growing population, such as hydroponics, which has shown potential in this aspect.

Hydroponics is the technique of growing plants in soilless cultures with their roots immersed in mineral rich nutrient solutions, often with the combination of inert growing media such as gravel, perlite, and cellulose or other mineral wool.[5] Hydroponics has advantages over soil growing by offering higher crop yields per area and can be used in places where traditional agricultural techniques cannot be used, such as desert areas, urban populations, and in cold climates. The system or environmental parameters of a hydroponic system, such as pH, electrical conductivity, CO_2, and temperature, can be controlled more precisely than other traditional agricultural methods, allowing hydroponic systems to use less water and nutrients decreasing the cost associated with those resources, and makes the system more efficient. Studies have shown that closed hydroponic systems that recirculate water use up to 90% less water than soil-based farming and increase the efficiency of used water by 250%.[6] Hydroponic systems also do not require pesticides and other toxic chemicals to kill insects, fungi, and bacteria, eliminating the contamination of water, and without a need for fallowing or tilling in between growth cycles which significantly reduces the energy, cost, and time of growing cycles.[7] All these reasons contribute to the increasing popularity of hydroponics in agricultural and horticulture practices including commercial agriculture, urban farming, and restoration ecology efforts. In the 2017 Census of Agriculture from the USDA, approximately 420 million pounds of food crops grown in closed environments (typically greenhouses) were produced from hydroponic systems, [8] a staggering increase from their 2012 Census when that metric was not included. [9]

Plant Biology Principles In A Hydroponics System

The structure and function of plant organs, tissues, and cells are closely related to their growth, development, and physiological processes. For example, the root structure influences nutrient and water absorption, stem structure affects water and nutrient transport, while leaf structure is crucial for photosynthesis and transpiration.[1,2] In hydroponic systems, the absence of soil and the direct exposure of roots to nutrient-rich water can impact root structure, nutrient uptake, and water regulation. Additionally, the availability of light, nutrient concentrations, pH levels, and other environmental factors in hydroponic systems can influence plant organ and tissue development, cellular characteristics, and physiological processes.[3,4]

In hydroponic systems, the control of light parameters (i.e. wavelength, intensity, and duration) and nutrient concentrations can be carefully managed to optimize photosynthetic rates and plant growth.[3,4] This allows for precise manipulation of the environmental factors that influence photosynthesis, providing an opportunity to enhance plant growth and overall hydroponic system efficiency. Nutrient solutions can be formulated to provide the exact concentrations of macronutrients and micronutrients that are required for optimal plant growth. Macronutrients are required in relatively large quantities by plants and play critical roles in various physiological processes: N, P, Ca, K.[5] Micronutrients, also known as trace elements, are required in smaller quantities by plants but are equally essential for their growth and development: Fe, Zn, Cu, Mn, Mo, B, and Cl.[5] This allows for fine-tuning of nutrient availability to meet the specific needs of different plant species, growth stages, and environmental conditions. Various environmental factors can significantly impact plant growth and development, and their control and optimization are crucial in a self-regulated hydroponic system. Some of these conditions include temperature, humidity, pH, air circulation, lighting, and carbon dioxide levels.[6-8]

Microgreens for Data Collection

Microgreens refer to the immature greens or seedlings produced from the seeds of vegetables, herbs or grains.[1] A unique feature of microgreens is their capacity for rapid growth and development in short periods of time. They are typically harvested at the base of the hypocotyls just after the cotyledon leaves and one set of true leaves have developed, usually between 7-21 days from seed germination depending on the species.[2]

Figure 1. Representative diagram of a microgreen identifying the cotyledon and upper hypocotyl as the edible portions and lower hypocotyl and the roots as the inedible portion.[7]

These short growing cycles are particularly valuable to research, as they create the opportunity for microgreens to be used as a model system for studying plant responses to changes in their environments and adaptations to different growing conditions. Their small size is another characteristic that makes microgreens well suited for research, as they can be grown in large quantities within a small area. Common methods for analyzing microgreen growth include assessment of nutrient content, total yield, harvest weights per unit time, stem heights, and leaf surface area.[4-6]

Advantage of an Automated Hydroponics System

A self-regulated hydroponic system would be classified as an advanced hydroponic system that utilizes an array of sensors, actuators, and control algorithms to monitor system parameters and control actuators to optimize plant growth. These systems are carefully designed to emulate an environment that can be closely monitored and controlled to enhance the efficiency, sustainability, and scalability of the system. In an autonomously regulated hydroponic system several different sensors are placed within to retrieve data on the system's environmental parameters, such as light intensity, air quality, climate conditions, nutrient concentrations, etc. This in combination with various control algorithms, which can be software uploaded to microcontrollers such as an Arduino, allows the system to control various actuators that adjust different environmental parameters. One benefit of an autonomously regulated system is that there is minimal need for manual interventions, which increases the precision and consistency of controlling the system's environmental conditions and minimizes the risk of human error.[1] Autonomously regulated hydroponic systems also have increased resource efficiency since the delivery of water, nutrients, and heat can be carefully monitored and closely controlled, improving its overall resource sustainability.[1] Not only that but these systems can be scaled to any size, whether for research or educational purposes or for larger commercial applications.

APPARATUS & METHODS

Senior Process Engineering Lab II (Unit Operations) is the continuation of a two-semester lab design course. Students are tasked with designing their own experiment, proposing it, and quantifying data. For this experiment, students used a fully automated hydroponics system (HydroPod) to maintain system parameters. The HydroPod is 4ft×3ft×6ft and a fully automated growing system that includes 36 trays split between two levels and lights with relative intensity of 4000K, 5000K and 6500K. The HydroPod also features Styrofoam barriers between trays of differing relative light intensities to prevent light contamination. The HydroPod controlled light intensity and duration of lighting.

The Hydropod regulated electroconductivity, pH, water temperature, and flow rates throughout each9-day grow season. The pH was maintained between 5.6 - 6.2, EC values above 2,100 µS/cm, and a water temperature of 30°C were maintained with the HydroPod. The growing environment remained regulated at 27°C for the air temperature.

Handy Pantry biodegradable wood fiber hydroponic grow pads were cut into 23.5 cm × 5 cm rectangles to fit within the vinyl growing trays. The grow pads were soaked in the system for 10 minutes for maximum water saturation, and the mass of the wet grow pad and tray was measured for each individual tray. The optimal seed density for mustard microgreens, found in previous studies, of 50 g/m^2 were weighed out and distributed uniformly on the growing mats where a PVC block was placed on top to encourage germination.[1] The seeds were allowed to germinate within the dark with applied pressure for 3 days and nutrient solution running at a 7.5 mL/min, before the blocks were removed. On the third day, light was provided to the plants, while the flow rate of the nutrient solution was kept at 7.5 mL/min. The nutrient solution consisted of 0.69 g/L of KNO_3, 0.54 g/L of $Ca_3(PO_4)_2$, 0.94 g/L of $MgSO_4$, 0.12 g/L of $(NH_4)_2SO_4$, 0.31 g/L of $CaH_4P_2O_8$, and 0.05 g/L of $FeSO_4$. On the fourth day, if flow rates was investigated were increased to 125 or 250 mL/min.

Measurement Techniques

After germination concluded on day 3, the trays were removed from the system once a day, allowing excess water to drain from the growing mats for 10 minutes before taking the wet weight and measuring stem length. Mass growth percentage was calculated using equation 1 and was based on the wet weight of each sample.

$$Mass\ Growth\ \% = \frac{Weight\ on\ day\ n - Seed\ weight}{Seed\ Weight} \tag{1}$$

The height of the microgreens was taken each day by measuring three sections of the growing tray and calculating the average. Nine days after germination began, the growing season was concluded, and microgreens were picked from the grow pads. The microgreens were placed in a conventional oven set to 150°F for an hour before being weighed to determine final dry weight. Prior to drying, visual parameters were noted such as color, progression of vegetable leaves (e.g. cotyledon and first true leaves), root length and density.

System Cleaning

At the end of a growth cycle, plants are removed from the growth medium, which is disposed of along with the remaining solution in the nutrient reservoir. Each tray, germination block, and microtube was scrubbed with hot water and a sponge or straw cleaner. The HydroPod was also scrubbed with hot water and then run with hot water for 15 minutes to remove debris within the pipes. All components inside the nutrient reservoir including heaters, pumps, sieves, and sensors were cleaned off with hot water and a sponge.

SAFETY

This experiment uses mild irritants which can be mitigated by wearing proper PPE.

RESULTS & DISCUSSION

Effect of nutrient solution composition on microgreen growth

Mustard microgreens were grown using two different media. One was a nutrient rich solution based on a common hydroponic solution recipe while the other was deionized water.[3] Figure 1 shows the differences in mass growth percentage based on nutrient solution composition.

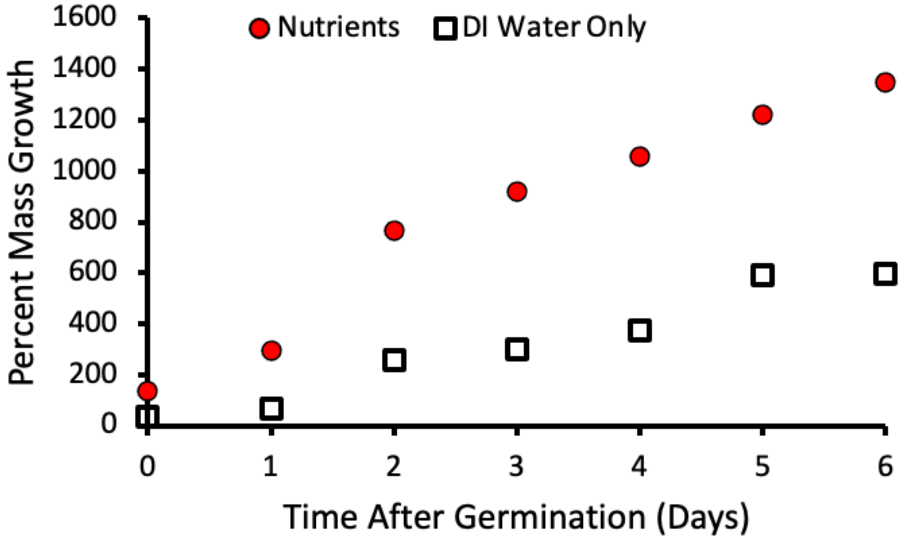

Figure 1. Percent mustard microgreen growth over time after germination when provided DI water (black squares) and a nutrient-rich solution with an electrical conducitivty of 2100µS/cm (red circles).

The results of this study confirmed the expectations that microgreens provided with the complete macro and micronutrients needed for growth and development in their nutrient solution have the increased capacity for growth and development in faster durations.As mentioned, the results of this study are expected because the nutrients provided in the mineral solution are required for several metabolic processes that are directly related to the ability for microgreens to grow and develop.[1,2] One such example of this is the concentration of Nitrogen, a required macronutrient by plants, in the nutrient solution. The concentration of nitrogen in the nutrient solution is significantly higher than the case of the mineral rich nutrient solution as compared to only DI water. Nitrogen, a macronutrient for plants, is essential for the development of amino acids which produce growth and metabolic enzymes in plants.[1,2] The concentration of growth and metabolic enzymes present in plant cells determines the plants' capacity for growth and development.[1] Therefore, it is hypothesized that the increase in the concentration of nitrogen available to the plants in the mineral rich nutrient solution, increased the development of growth and metabolic enzymes, which in turn increases the concentration of these enzymes in plant cells, and thus increases the capacity for the plant to grow and develop.[1] Another example lies in the requirements of micronutrients for plant growth. Magnesium is an essential micronutrient for plants, and it is a requirement to form photosynthetic pigments such as chlorophyl.[2] The concentration of chlorophyl in plants cells is related to the photosynthetic activity of the plant cells, which determines the rate of photosynthesis.[2] The rate of growth and development by plants is determined by the rate of photosynthesis in the plant cells.[2] Therefore, it is hypothesized that the increase in micronutrients in the mineral rich solution increases the concentration of photosynthetic pigments in the plant cells, and hence increases the growth and development of the plants as the plants cells have an increase in photosynthetic activity.[2]

Flow Rates

Plants tend to morphologically adapt to their environments, including varying their root length, roots per plant, and root surface area.[1] With lower flow rates nutrients have a much larger residence time in the system compared to higher flow rates.Figure 2 shows the percent mass growth of mustard microgreens at different nutrient flow rates.

Figure 2. Percent mass growth of mustard microgreens over time at flow rates of 7.5 mL/min (red triangle), 125 mL/min (black square), 250 mL/min (blue circle).

The 7.5 mL/min flow rate allowed for the nutrients to pass through the mats slower, causing the microgreens to be exposed to the nutrients for a longer period of time. 125 mL/min low rate flushed out nutrients much quicker than the low flow rate which does not allow for the maximum uptake of nutrient although it does replenish them quicker. 250 mL/min flow rate flooded the plants and put constant strain on the seeds to try to attach to the mat which was deteriorating as well. This flow rate was too quick to allow the microgreens to absorb the nutrients as well as with the excess of water in the tray caused mold and other diseases to become present, ultimately hindering the growth of the microgreens.[2]

Relative Light Intensity

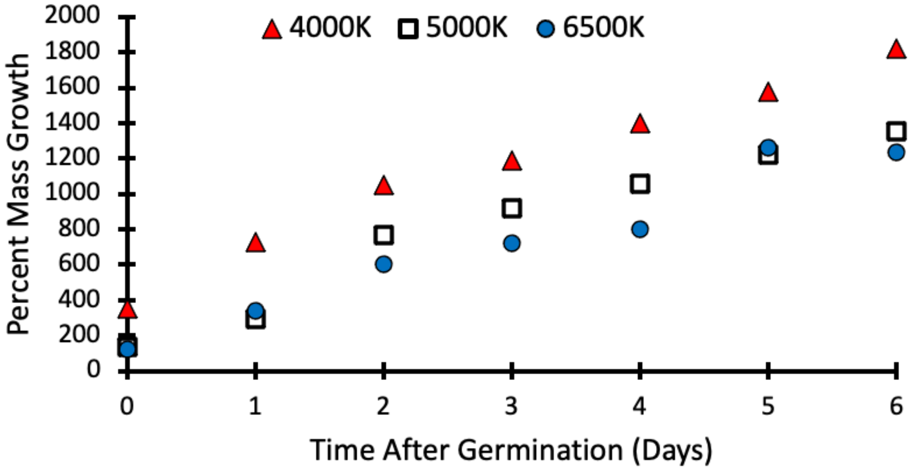

Figure 3. Percent mass growth of mustard microgreens over time with relative light intensities of 4000K (red triangle), 5000K (black square), and 6500K (blue circle).

As shown in Figure 3, the mass percentage for the different relative intensities of grow lights used demonstrated that the 4000K light had the highest mass growth percentage. Stem lengths of microgreens exposed to higher concentrations of red photons were found to be slightly longer than those exposed to lower red photon concentrations. Adversely, it was found that microgreens exposed to a higher concentration of blue photons had slightly larger leaves.

Seed Density

As shown in Figure 4, the mass growth percentage across seed densities varying from 35 to 100 g/m^2 is shown in the figure above. The optimal seed density found in previous studies (50 g/m^2) was found to perform best. At seed densities much higher than this, 100g/m^2, the competition for nutrients, water and dissolved oxygen has a large effect on the uniform growth of the microgreens.

Figure #. Mass growth percentage of mustard microgreens with seed densities of 35 g/m^2 (blue triangle), 50 g/m^2 (black circle), 65 g/m^2 (red square), and 100 g/m^2 (pink diamond)

Due to there being more microgreens, there is also competition for sunlight, which results in some plants growing much taller than others. In addition to competition, at higher seed densities plants grow much less roots per plant as well as shorter roots due to the compaction caused by high densities.[2] At lower seed densities, such as 35 g/m^2, competition for nutrients is not as much of a problem as in higher densities. Lower densities allow the microgreens to morphologically adapt to grow longer roots and more roots per microgreen.[3] This increases the surface area of the roots and allows for a greater nutrient uptake in comparison to higher seed densities where the adaptation of the roots causes them to become shorter. Based off the findings in this experiment it would be argued that 35 g/m^2 would be the most optimal density to grown mustard microgreens.

Discussion

By setting up a lab which offered students the ability to design their own experiment, the hydroponics lab was able to accomplish many of the teaching goals incorporated in a unit process course. Ideally, within the semester-long senior lab course, students should be able to collect replicable and quantifiable data, test hypotheses by varying different parameters, and evaluate trends. The hydroponics microgreen experiment is one way students can complete these learning objectives in a cost-effective and timely manner. In one semester, students are expected to use two to do research to design their experiment. The microgreens used in this hydroponics experiment catered to the need for fast data collection as they are harvested in 7 to 10 days. This allowed students to collect data for five to seven grow cycles. By using microgreens, grow trays were able to be close together and therefore by using the HydroPod the second design criteria were adhered to as the data could be collected in replicate. Students in their research stage found common data collection techniques when observing plant growth. The data collection was fitted to best support the students' objectives of observing many variables and their growth effects on microgreens as well as the complexity of the method used. By using wet weight, height, and dry weight students were able to quantify data in a way that would allow them to show the results necessary as well as not overcomplicate. The final design criteria of varying data accomplished through the design of the experiments where multiple parameters could be changed.

CONCLUDING REMARKS

As alluded to by the NAS, an emerging field that chemical engineers should enter is plant growth in sustainable systems. Here, students demonstrated success in investigating the effects of several growth conditions on microgreen growth. In two weeks, students collected quantifiable data for five conditions in triplicate that demonstrated significant differences between several variables. When performing this microgreen growth experiment students worked with minimally hazardous chemicals that at most are mild irritants. The estimated operating cost per semester is $150 which includes microgreen seeds, grow mats, nutrient solution salts, pH regulators, and replacement equipment which are all easily purchased items. This experiment provides flexibility so that a single group can complete a multitude of experiments within a semester, or it can be adapted for multiple groups to use the system throughout the semester, so that groups can build on data from preceding groups. The flexibility of this lab experiment allowed students to spend about one hour a day for 9 days in lab collecting data compared to the typical way PELII is conducted with five 5-hour lab sessions.

For chemical engineers, microgreen growth applies a variety of chemical engineering concepts such as: material and energy balances, fluid dynamics, heat and mass transfer, reaction kinetics, and process control. Although this experiment was tested in a senior unit operations course, it shows potential to be applied in a variety of other undergraduate courses as a lab experiment or demonstration. It can also be utilized to help with teaching and assess any of the ABET student outcomes, especially outcomes 2 and 4 which focus on producing solutions and making informed judgements in consideration for the impact on public health, safety, global and environmental contexts. By the hydroponics experiment touching upon the ABET outcomes in addition to offering a hands-on learning experiment makes it a highly useful laboratory experiment which prepares students for their futures.

ChE can be described as the engineering of systems or processes. For an autonomously regulated hydroponic system there are several fundamental concepts and principles that are relevant to the ChE curricula. Not only does the process of researching, designing, building, and collecting data with an autonomously regulated hydroponic system encompass the essence of engineering, but the process requires an understanding and application of concepts such as mass and energy balances, fluid dynamics, heat and mass transfer, reaction kinetics, process control and design, amongst others. The application of these principles to these systems can allow for system optimization which can decrease energy and/or resource use, and severally decrease the cost of system operation.

References & Acknowledgements:

Intro

1. Peppas, N. A. The Origins of Academic Chemical Engineering. *One Hundred Years of Chemical Engineering* **1989**, 1–14.
2. Varma, A. FUTURE DIRECTIONS IN CHE EDUCATION: A New Path to Glory *Chemical Engineering Education* **2003**, 37.
3. Qian, Y.; Vaddiraju, S.; Khan, F. Safety Education 4.0 – A Critical Review and a Response to the Process Industry 4.0 Need in Chemical Engineering Curriculum. *Safety Science* **2023**, *161*, 106069.
4. Westwater, J. W. The Beginnings of Chemical Engineering Education in the USA. *Advances in Chemistry* **1980**, 141–152.
5. *Chemical Engineering in the pharmaceutical industry: R & D to manufacturing*; Wiley: Hoboken, 2011.
6. Top Pharmaceuticals. *Chemical & Engineering News Archive* **2005**, *83* (25), 27.
7. New Directions for Chemical Engineering. *National Academy of Sciences* **2022**.
8. Shaffer, J. How Chemical Engineering Students Feel about Biology. *Chemical Engineering Education* **2023**, *57* (1).
9. Gautam, S.; Nagarajan, K.; Loh, K. C.; Zhou, K.; Yung, L. L. Y.; Tong, Y. W.; Li, Z. Hands-On Learning: An Experiential Approach to Train Chemical Engineering Students. *Chemical Engineering Education* **2020**, 54(2).
10. Alkaya, D.; Cruz, R. V. A. da; Grossmann, I. E.; Provine, W. D.; Silverstein, D. L.; Steininger II, R. J.; Talbot, J. B.; Varma, A.; McCreight, T.; Chin, K.; et al. Chemical Engineering Academia-Industry Alignment: Expectations about New Graduates. *American Institute of Chemical Engineering* **2015.**
11. Dahlstrom, D. A. CHEMICAL ENGINEERING Notes on Its Past and Its Future. *Chemical Engineering Education* **1994,** 28(4).

B&T Traditional

1. Marchal, V.; Dellink, R.; van Vuuren, D. van V.; Clapp, C.; Château, J.; Lanzi, E.; Magné, B.; van Vliet, J. OECD Environmental Outlook to 2050. *OECD Environmental Outlook* **2012**.
2. Connor, R. The United Nations World Water Development Report 2023. *The United Nations World Water Development Report* **2023**.
3. Howell, T. Irrigation Efficiency. *Irrigation Engineering* **2022**, 286–298.

4. West, T. O.; Marland, G. A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States. *Agriculture, Ecosystems & Environment* **2002**, *91* (1-3), 217–232.
5. Roberto, K. *How-to hydroponics*; Electron Alchemy, Inc.: Massapequa, NY, 2014.
6. AlShrouf, A. Hydroponics, Aeroponic and Aquaponic As Compared With Conventional Farming. *ASRJETS-Journal* **2017**, *27*, 247-255.
7. United States Department of Agriculture https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Census_of_Horticulture_Specialties/index.php (accessed May 5, 2023).
8. United States Department of Agriculture https://www.nass.usda.gov/AgCensus/ (accessed May 5, 2023).

B&T Microgreens

1. Renna, M.; Paradiso, V. M. Ongoing research on microgreens: Nutritional properties, shelf-life, sustainable production, innovative growing and processing approaches. *Foods* **2020**, *9* (6), 826.
2. Bhaswant, M.; Shanmugam, D. K.; Miyazawa, T.; Abe, C.; Miyazawa, T. Microgreens—a comprehensive review of bioactive molecules and health benefits. *Molecules* **2023**, *28* (2), 867.
3. Kan, J.; Wu, F.; Wang, F.; Zheng, J.; Cheng, J.; Li, Y.; Yang, Y.; Du, J. Phytonutrients: Sources, bioavailability, interaction with gut microbiota, and their impacts on human health. *Frontiers in Nutrition* **2022**, *9*.
4. Kowitcharoen, L.; Phornvillay, S.; Lekkham, P.; Pongprasert, N.; Srilaong, V. Bioactive composition and nutritional profile of microgreens cultivated in Thailand. *Applied Sciences* **2021**, *11* (17), 7981.
5. Di Gioia, F.; De Bellis, P.; Mininni, C.; Santamaria, P.; Serio, F. Physicochemical, agronomical and microbiological evaluation of alternative growing media for the production of Rapini (*brassica rapa*L.) microgreens. *Journal of the Science of Food and Agriculture* **2016**, *97* (4), 1212–1219.
6. Keutgen, N.; Hausknecht, M.; Tomaszewska-Sowa, M.; Keutgen, A. J. Nutritional and sensory quality of two types of cress microgreens depending on the mineral nutrition. *Agronomy* **2021**, *11* (6), 1110.

B&T Automated

1. Isabel Luna Maldonado, A.; Mariana Márquez Reyes, J.; Flores Breceda, H.; Rodríguez Fuentes, H.; Antonio Vidales Contreras, J.; Luna Maldonado, U. Automation and robotics used in Hydroponic System. *Urban Horticulture - Necessity of the Future* **2020**.
2.

Plant bio

1. Rogers, E. D.; Benfey, P. N. Regulation of Plant Root System Architecture: Implications for Crop Advancement. *Current Opinion in Biotechnology* **2015**, *32*, 93–98.

2. Wang, Y. P.; Jarvis, P. G. Influence of crown structural properties on par absorption, photosynthesis, and transpiration in sitka spruce: Application of a model (maestro). *Tree Physiology* **1990**, *7* (1-2-3-4), 297–316.
3. Fimbres-Acedo, Y. E.; Traversari, S.; Cacini, S.; Costamagna, G.; Ginepro, M.; Massa, D. Testing the effect of high ph and low nutrient concentration on four leafy vegetables in hydroponics. *Agronomy* **2022**, *13* (1), 41.
4. Chiang, C.; Bånkestad, D.; Hoch, G. Reaching natural growth: Light quality effects on plant performance in indoor growth facilities https://www.mdpi.com/2223-7747/9/10/1273 (accessed May 5, 2023).
5. Fan, X.; Zhou, X.; Chen, H.; Tang, M.; Xie, X. Cross-talks between macro- and micronutrient uptake and signaling in plants. *Frontiers in Plant Science* **2021**, *12*.
6. Baiyin, B.; Tagawa, K.; Yamada, M.; Wang, X.; Yamada, S.; Yamamoto, S.; Ibaraki, Y. Study on plant growth and nutrient uptake under different aeration intensity in hydroponics with the application of particle image velocimetry. *Agriculture* **2021**, *11* (11), 1140.
7. Chia, S. Y.; Lim, M. W. A critical review on the influence of humidity for plant growth forecasting. *IOP Conference Series: Materials Science and Engineering* **2022**, *1257* (1), 012001.
8. Lamichaney, A.; Tewari, K.; Basu, P. S.; Katiyar, P. K.; Singh, N. P. Effect of elevated carbon-dioxide on plant growth, physiology, yield and seed quality of chickpea (Cicer arietinum L.) in Indo-Gangetic Plains. *Physiology and Molecular Biology of Plants* **2021**, *27* (2), 251–263.

Lab experiment

A&M

1. Nolan, D. A. Effects of Seed Density and Other Factors on the Yield of Microgreens Grown Hydroponically on Burlap. **2018**.
2.

Safety

R&D

Nut

1. Lea, P. J.; Azevedo, R. A. Nitrogen Use Efficiency. 2. Amino Acid Metabolism. *Annals of Applied Biology* **2007**, *151* (3), 269–275.
2. Sánchez, E.; Berghage, R.; Ford, T.; Gioia. F. D. *Hydroponics systems and principles of Plant Nutrition: Essential Nutrients, function, deficiency, and excess.* Penn State University **2023.** https://extension.psu.edu/hydroponics-systems-and-principles-of-plant-nutrition-essential-nutrients-function-deficiency-and-excess (accessed Apr 30, 2023).

Flow

1. Baiyin, B.; Tagawa, K.; Yamada, M.; Wang, X.; Yamada, S.; Shao, Y.; An, P.; Yamamoto, S.; Ibaraki, Y. *Effect of nutrient solution flow rate on hydroponic plant growth and Root Morphology*. Plants **2021**, 10 (9), 1840.
2. Al-Tawaha, A. R.; Al-Karaki, G.; Al-Tawaha, A. R.; Sirajuddin, S. N.; Makhadmeh, I.; Wahab, P. E. M.; Youssef, R. A.; Sultan, W. A.; Massadeh, A. Effect of water flow rate on quantity and quality of lettuce (Lactuca sativa L.) in nutrient film technique (NFT) under hydroponics conditions. *Bulgarian Journal of Agricultural Science* **2018**, *24* (5), 793–800.

Lights

1. Sun, J.; Nishio, J. N.; Vogelmann, T. C. Green Light Drives CO2 Fixation Deep within Leaves. *Plant and Cell Physiology* **1998**, *39* (10), 1020–1026.
2. Pettai, H.; Oja, V.; Freiberg, A.; Laisk, A. Photosynthetic Activity of Far-Red Light in Green Plants. *Biochimica et Biophysica Acta (BBA) - Bioenergetics* **2005**, *1708* (3), 311–321.
3. Wang, J.; Lu, W.; Tong, Y.; Yang, Q. Leaf Morphology, Photosynthetic Performance, Chlorophyll Fluorescence, Stomatal Development of Lettuce (Lactuca Sativa L.) Exposed to Different Ratios of Red Light to Blue Light. *Frontiers in Plant Science* **2016**, *7*.

Density

1. Nolan, D. A. *Effects of Seed Density and Other Factors on the Yield of Microgreens Grown Hydroponically on Burlap*. **2018**.
2. Bar-Tal, A.; Ganmore-Neumann, R.; Ben-Hayyim, G. *Root architecture effects on nutrient uptake. Biology of Root Formation and Development* **1997**, 39–45.
3. Baiyin, B.; Tagawa, K.; Yamada, M.; Wang, X.; Yamada, S.; Shao, Y.; An, P.; Yamamoto, S.; Ibaraki, Y. *Effect of nutrient solution flow rate on hydroponic plant growth and Root Morphology. Plants* **2021**, 10 (9), 1840.
4.

Conclusion

4. Anonymous. Abet https://che.engineering.ucdavis.edu/undergraduate/abet (accessed May 5, 2023).