Bioreactor Design, Automation and Optimization - A Multidisciplinary Approach

Dr. Vassilios Tzouanas, University of Houston, Downtown

Vassilios Tzouanas is an Associate Professor and Chairman of the Computer Science and Engineering Technology department at the University of Houston – Downtown, in Houston, Texas. He received all his degrees in chemical engineering and obtained his Ph.D. from Lehigh University. He has worked in the industry for 19 years where he held technical and management positions with major operating companies as well as process control technology development companies. Since 2010, he has been with UHD. Dr. Tzouanas' research interests include process modeling, simulation and design, process control, and renewable energy systems. Dr. Tzouanas is an ABET Program Evaluator (PEV) for Engineering and Engineering Technology programs. He is also member of AIChE and ASEE, and currently serves as ETD Director.

Dr. Lisa Deane Morano, University of Houston-Downtown

Lisa Morano is a Professor of Biology and Microbiology at the University of Houston-Downtown (UHD). She is also the Director of the Center for Urban Agriculture and Sustainability (CUAS) at UHD. Her research has focused on the bacteria found inside plants including plant pathogens and non-pathogenic inhabitants called endophytes. Her research has also included multiple USDA-NIFA funded programs that have led to the creation of new curriculum and experiential learning opportunities through the CUAS. She teaches multiple courses in environmental biology and sustainability and she organizes an experiential learning program where students work in teams to build solar-powered technology that addresses a need in urban agriculture.

Hung Pham
Mr. Anish Khatiwada, University of Houston-downtown

Anish Khatiwada graduated with Suma Cum Laude honors from the University of Houston - Downtown with a Bachelor's in science in the year of 2015. Anish majored in Control and Instrumentation Engineering Technology and has a minor in Mathematics. Anish was a member of the Scholars Academy while attending the University of Houston – Downtown. He was recipient of the Red Rose Scholarship. Currently, Anish is a Sr. Software Engineer at Automation Nation, Inc.

Mr. Jonathan Lopez

Bioreactor Design, Automation and Optimization – A Multidisciplinary Approach

I. Abstract

Students from our engineering technology, biology, and safety management programs developed a bioreactor to produce bioethanol from various organic wastes. Bioethanol can also be made from corn, potatoes, rice, beetroot and recently grapes. However, making bioethanol from crops negatively impacts the availability of such products for food consumption. By using organic waste, this project ensures sustainable consumption and production patterns. Converting waste to bioethanol creates a fuel from a biomass that would have been energetically wasted during the decomposition process. Using bioethanol or blending it with gasoline both reduce the reliance on fossil fuel and ultimately reduce the carbon dioxide entering the atmosphere. Thus, it is a truly sustainable transport fuel.

In this paper, the design of the bioreactor, instrumentation and automation mechanisms are presented. Kinetics studies and the results from the optimization of the reactor operating conditions area also discussed. Since such work also was carried out as part of engineering technology students' senior capstone project, lessons on project management, budget and schedule development, teamwork, and technical communication will also be presented. Process data were analyzed by biology students to estimate the amount of ethanol produced under various operating scenarios. Biology students also had primary responsibility for selecting and preparing the bioreactor feedstocks. The contributions of the safety management students emphasized to the team the importance of considering safety as part of the design and operation of a process.

This multi-disciplinary project emphasizes important aspects of an education that will assist students in the real world. Students must master the language of other disciplines, work together to design and build a system and make sure the system meets the original goals set by the project. Such programs could be a model for the future, high-impact, cross-disciplinary direction of engineering technology education.

II. Introduction

For the first time in the history of the planet one species has dramatically altered the planet. As of 2020 there are 7.8 billion people on Earth[1] and an ever increasing need for resources to run our economies and our agricultural systems. Globally humans are converting wild ecosystems into agricultural land and utilizing more freshwater for food production. On top of ecosystem loss we need to figure out ways to stabilize the ecosystems that remain so that they may continue to provide the services we need such as climate stabilization, water collection and purification and pollination of our food[2]. The future global economy will need to focus not just on growth, but sustainable growth that allows for a human future that is economically solvent and environmentally sound. Considering educational structures that will combine an appreciation of the issues and skills to design the technologies to address these problems should be a central goal of our universities.

There are now more humans in cities than in rural areas and the future of human growth will continue to be in urban centers. Cities are an efficient place to support growing human populations with respect to infrastructure needed, energy needed per person and therefore produce a smaller carbon footprint produced per person. There is also a great deal of research on how urban centers can both grow and become more energetically sustainable[3]. Sustainable cities of the future will require urban planners, scientists and engineers to work together to optimize renewable energy production that works for that region. There is also a great deal of current work on developing a city-integrated collection of renewable energies appropriate for the city location[4]. Biofuels are considered one component of creating sustainable energy systems for urban centers (along with solar, wind and in some areas geothermal) [5].

Biofuels include any fuel that can be produced by living organisms. Usually, however, the term implies the production of ethanol produced from the fermentation of plant materials and then distilled for fuel. The plant materials to be used for biofuels categorically fall into high sugar or starch materials as is found in sugarcane or grains of wheat, corn, or rice. These materials are obviously easy to convert into alcohol. Another category of materials under intense investigation is the use of plant waste material for conversion to ethanol. The advantage of this second type of material is that you are not pitting the future production of energy against the future production of food. As fresh water and available agricultural land become more limited using plant waste to produce fuel seems like a sustainable solution to the overall energy production plan for cities. A disadvantage of using these plant-based wastes is that they are high in cellulose and lignocellulose plant compounds that are more difficult to breakdown than simple starches. Ethanol production from these plant wastes is called second-generation bioethanol production[6].

Like all future problems that this earth faces technology will play a central role in solving the problems. However, the scientists and engineers will need to work collaboratively to figure out which technologies to pursue and to monitor which are really making a difference. Although this need for collaboration is well-acknowledged in both industry and public agencies, structural components of academia make collaborations of programs or departments difficult[7]. Pressure to graduate students in programs with less hours means less electives and less flexibility for students to learn information outside their discipline. Faculty performance review committees struggle to evaluate activities outside the expertise of the department and high faculty workload makes for a high activation energy for cross-disciplinary collaborations. These challenges can be barriers for valuable opportunities for students and faculty. This project demonstrates the enormous value of such collaborations and the rewards of engaging in cross-disciplinary research.

This project had a goal of engaging students from different disciplines into a project of mastering the fermentation process behind biofuel production. Students in a Senior Projects Engineering Technology (ET) course designed different bioreactors – one that was completely built from scratch and others that used a starting glass bioreactor vessel. In the last ET team there was also a Safety Management major so he was tasked with overseeing safety aspects of design and implementation. Students in a junior-level microbiology class (Environmental Microbiology) used the bioreactors for microbiological fermentation experiments as part of a group project. Although the focus of the project could have been to teach the basics of fermentation for any industrial process we chose to focus on students on the value of bioreactors for assisting in energy production. Students in the Environmental Microbiology combined their experiment with a presentation on some aspect of fermentation that was relevant to making future food or energy production more sustainable. In other words, students ran experiments in simple fermentation, but were then challenged to consider the challenges and benefits of future experiments where biological wastes could be converted to bioethanol via second-generation bioethanol production.

The paper is organized as follows. Section III presents the bioreactor systems and provides technical details on the methods and materials used to build them. Section IV summarizes experimental data for various feed-stocks while Section V talks about the learning outcomes and VI about project safety. Instead of conclusions, Section VII summarizes take away messages and is followed by Acknowledgements and References.

III. Design and Automation of the Bioreactors

In simple terms, a bioreactor is a vessel where the conversion of raw materials into new products takes place under controlled operating conditions. There are different types of bioreactors: continuous, batch and semi-batch. In this project, three batch bioreactors were designed, constructed and automated. The feedstock of the reactors was fruit juice so that fermentation of glucose into ethanol could proceed without special substrate treatment.

Engineering technology students designed and automated the operation of the bioreactors as part of their senior capstone project. This project took three different teams of engineering technology students over a period of three academic semesters to complete all three reactors. During one of the later semesters the ET students worked closely with biology students in Environmental Microbiology. Together, the students in both disciplines were responsible for monitoring feedstock, defining operating conditions, and calculating the ethanol content of the product.

The first bioreactor (Bioreactor 1) did not use any prefabricated components. The students identified all components and put them together in a working and completely functional system. This bioreactor is shown in Figure 1. For the other two bioreactors, the vessel was prefabricated. The reactors came also with a motor for mixing the reactor contents and primitive temperature control mechanisms (see Figure 2).

 

Figure 1: Bioreactor 1 **Figure 2: Bioreactor – 2**

The ET students worked to fully automate the two pre-fabricated reactors (Figure 2). Students had the opportunity to design and implement different control strategies (such as cascade control and split range control) and to use a computer platform that is widely used in the industry. Students implemented the control strategies using a programmable logic controller (PLC) which was not part of the purchased pre-fabricated reactor parts. Figure 3 shows the fully automated, using a PLC, Bioreactors 2 and 3.

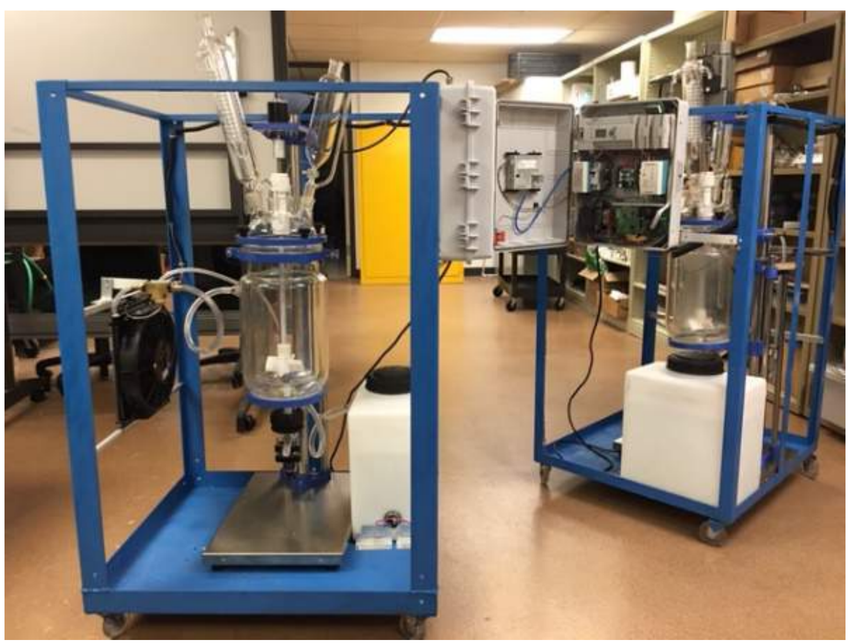

Figure 3: Bioreactors 2 and 3 with PLC based automation

The following paragraphs provide some details on the design and control strategies.

For Bioreactor-1, the design consists of one fermenter tank, one cultivation tank, one feedstock tank, and a single heating and cooling (H&C) water tank (Figure 4). The loading of feedstock and yeast into the fermenter tank, based on operating conditions specified, is fully automated.

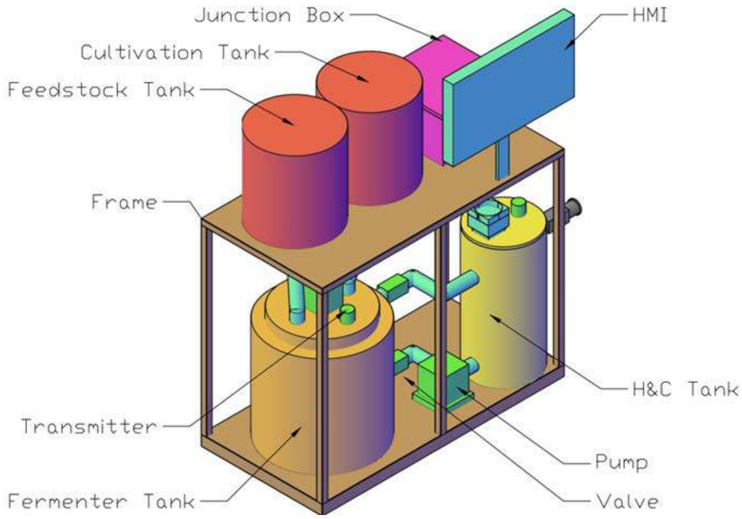

Figure 4: Schematic of Bioreactor-1 Design

To assist in the opening and closing of different process lines, solenoid valves are used throughout the system. These valves open and close automatically based on the set operating conditions and controller programming. During the fermentation process, the temperature, pressure, level, and CO_2 concentration of the fermentation tank are measured and data logged in real time.

In the Human-Machine Interface (HMI), trends of the pressure, temperature, level, and CO_2 concentration are displayed. The HMI also includes the various controls for the operator's desired amount of feedstock and yeast loaded to the fermenter tank, fermenter tank temperature, agitator speed, and process length of time.

The fermenter is submerged in a water bath which serves the purpose of a jacket. The temperature of the fermenter tank is controlled by continuously circulating water, at constant flowrate, through the reactor jacket from the Heating and Cooling (H&C) water tank. The temperature of the water inside the Heating & Cooling (H&C) tank is maintained either by heating or cooling it. The water is heated using a heating element that is in direct contact with the water and is cooled with the help of a Peltier thermoelectric module. During the fermentation process, samples of the reaction mixture can be drawn from the fermenter tank through a sample valve. Figure 5 shows the fully instrumented bioreactor and associated control strategies.

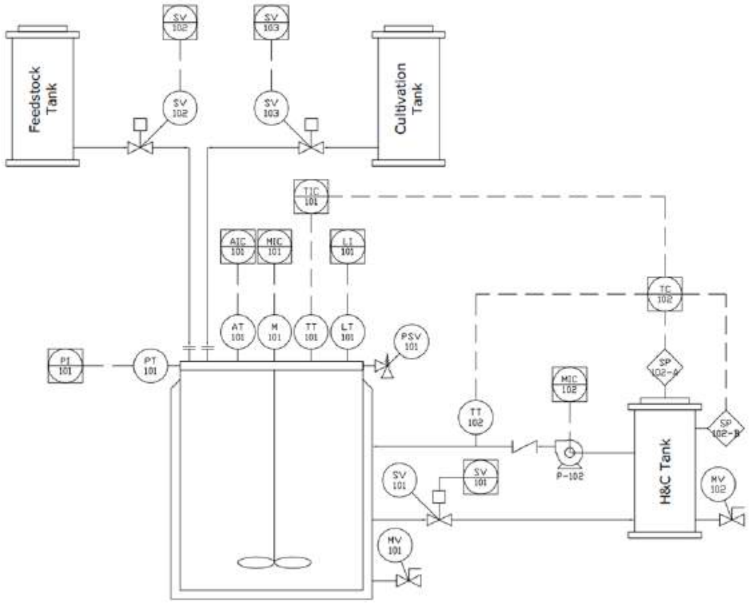

Figure 5: Schematic of Bioreactor-1 with Instrumentation and Control Strategies

The reactor temperature controller is of the on/off type also known as two position control. To minimize cycling and prevent damage to the heating and Peltier cooling elements, hysteresis was added to the controller operation to prevent the output from chattering[ML1]. To prevent overpressure and keep the fermenter at a certain pressure threshold, a solenoid valve was set to open every time the pressure reaches a maximum allowable limit. The automation strategies and HMI have been programmed using LabVIEW interfaced with myRIO for data acquisition. Figure 6 shows details of the HMI.

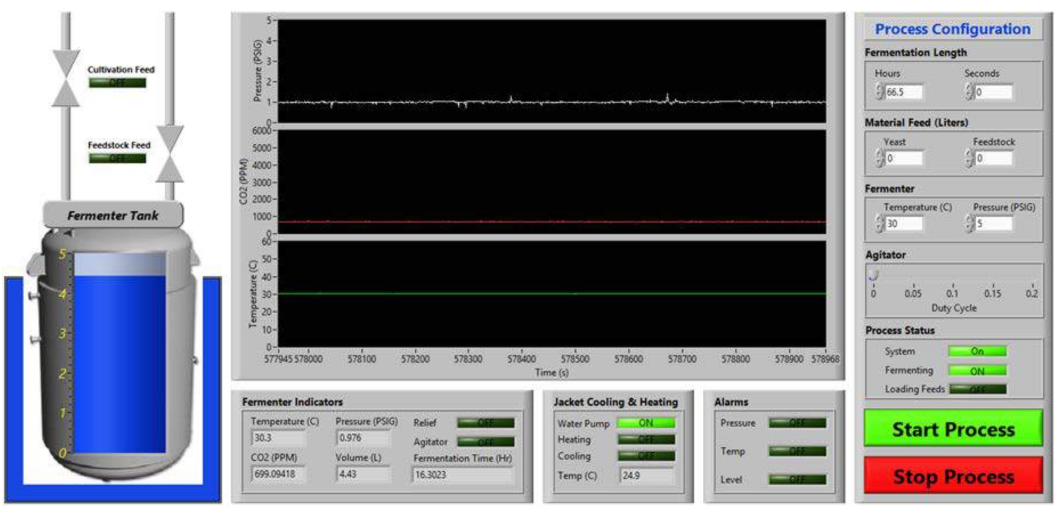

Figure 6: Bioreactor-1 Human Machine Interface (HMI)

In their latest version, Bioreactors 2 and 3 are fully automated using an Allen Bradley PLC as mentioned earlier (see Figure 3). The control structure is shown in Figure 7 and involves a combination of cascade control and split range control. The reactor temperature is controlled by adjusting the setpoint of the reactor jacket water temperature. The reactor jacket water temperature is controlled by adjusting the heating element or the fan speed in a split range configuration.

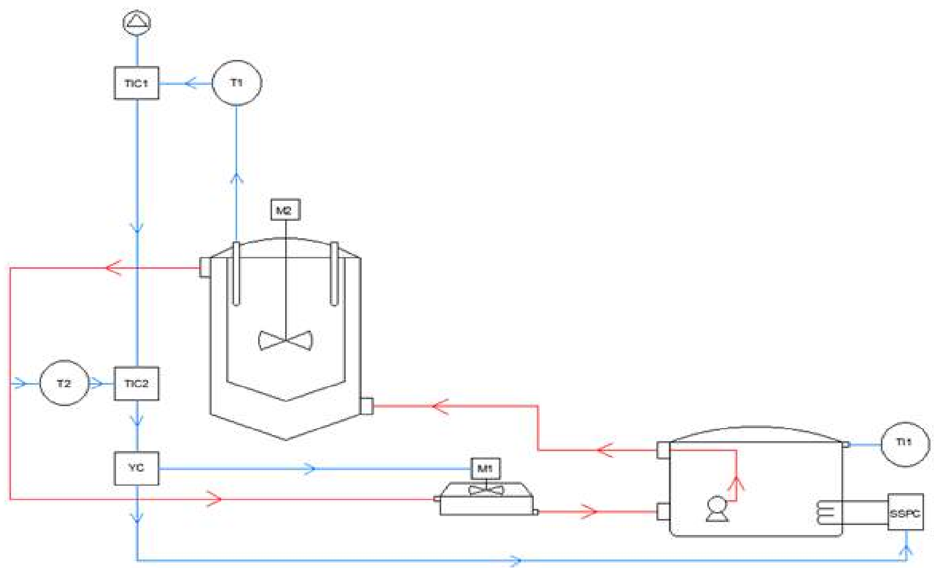

Figure 7: Bioreactor-2 and 3 Control Structure

IV. Experiments Using Feedstock

Biology students in the Environmental Microbiology course were put into 6 groups so that they could run replicate experiments in the two reactor systems. For this initial analysis of bioreactor function, the groups of students analyzed the rate at which alcohol was produced in each system using apple juice and yeast. Biology students were responsible for explaining the process and mechanism of fermentation to the class as part of their end of semester oral presentation. They needed to understand why cells engage in the fermentation process and why the reaction produces CO_2. The biochemistry of the reaction explains why CO_2 production rates are a good indication of overall fermentation rate. Fermenting juice samples were removed after approximately every 12 hours and tested in a hydrometer for specific gravity. Figure 8 shows plots of specific gravity for the two reactor systems at two temperatures. Lines B1_27 and B2_27, refer to bioreactors 1 and 2 respectively. In both reactor runs, the temperature was 27 C. Line B2_30 refers to bioreactor 2 when its temperature was 30 C. Based on the trend lines in Figure 8, it was concluded that the fermentation process lasts 2 to 2.5 days. There is no significant difference in the change of the specific gravity when the reactors run at 27 C or 30 C. Small differences early in the fermentation process are likely attributed to the fact that samples were collected and measured by different teams of students.

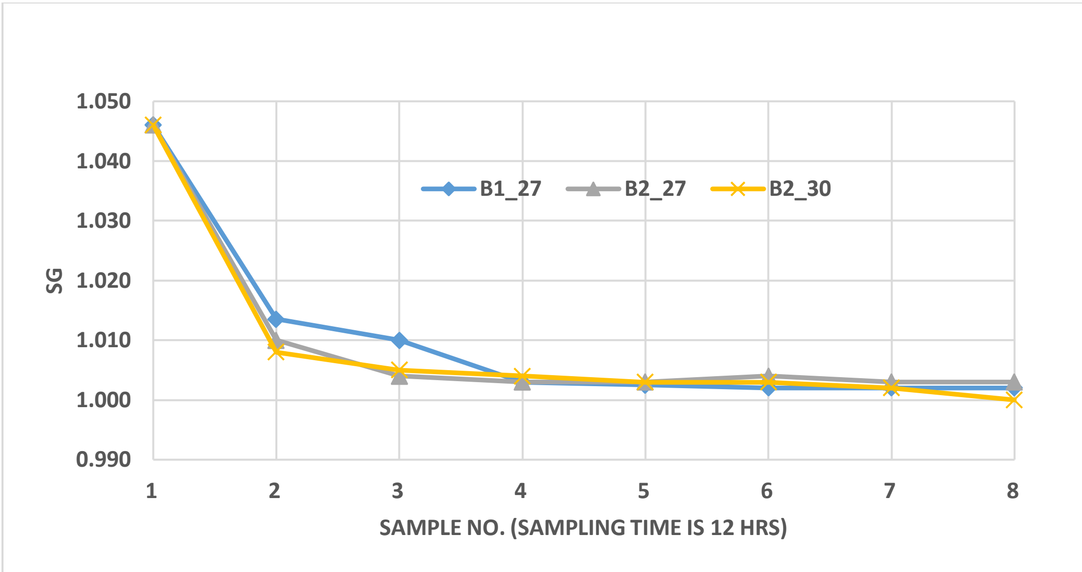

Figure 8: Specific gravity data as a function of time at both 27 and 30 degrees Celsius

The specific gravity measurements can be used to calculate a final percent alcohol. This is based on the fact that sugars in solution have a high specific gravity, but alcohol does not. The conversion of specific gravity drop into alcohol concentration is well-established by the fermentation industry. The biology students from Environmental Microbiology had to include results of their batch fermentation into end-of-semester group presentations. Each microbiology group gave a presentation on some aspect of fermentation in industrial bioreactors or specific promising new microbial species as part of a solution in sustainability. Table 1 shows changes in specific gravity for the reaction mixture between the start and the end of the fermentation process. Table 1 also shows the alcohol by volume content obtained at the end of the fermentation process.

Table 1: Fermentation Results (apple juice)

Group	Bio-Reactor	T (C)	SG Difference	Alcohol By Volume (%)
1	B1	27	0.044	5.78
2	B1	27	0.043	5.64
3	B2	27	0.042	5.51
4	B1	30	0.046	6.04
5	B1	30	0.043	5.64
6	B2	30	0.044	5.78

Following the experiments with juice some preliminary experiments were completed using model organic waste. For the organic waste experiment banana peels were blended and placed in the bioreactor for fermentation. Given the low concentration of sugar in waste the alcohol was significantly lower, about 2%. This is about a third of the alcohol concentration attained with juice. However, this low percentage of alcohol is energy that would otherwise be lost from the agricultural production system. With efficient industrial distillation process this could be a valuable resource. Student experiments with organic waste need to be replicated. In addition, we are considering having students add enzymes to assist in the breakdown of cellulose and other complex plant materials. This should increase the alcohol production levels.

V. Learning Outcomes

This project not only accomplished the goals of having students from different disciplines working together to optimize the fermentation process in bioreactors. This project also met all the requirements established at our university for a high-impact practice (HIP). The project had students spend extensive time-on-task in both courses. The creation and optimization of the industrial grade bioreactors was the focus of the group of engineering students assigned to this project. These students were required to generate a pre-proposal and budget, a full project proposal and a final oral presentation. This collaboration was also part of a semester-long project in Environmental Microbiology worth 100 points. The final assignments in both courses include both written and oral communication components. Below, in Table 2, are the Learning Outcomes for students involved in the collaboration and the assessment strategy for that learning outcome. In the table below the courses are referred to by their course numbers. Senior project course in Engineering Technology is course ENGR 4328 and Environmental Microbiology is MBIO 3340.

Table -2: Learning Outcomes and Assessment Strategies

Learning Outcome Students who complete the HIP's activity will be able to:	**Assessment Strategy**
Design and optimize a technology in order to solve a problem or serve a need.	Students in ENGR 4328 will be assessed on the design and optimization of the bioreactors.
Design and conduct experiments using the scientific method.	Students in MBIO 3340 will be evaluated for the quality of the scientific experiment they run and the statistical analysis they run.

Communicate orally and in writing by giving an effective presentation to the course and a quality final report.	An oral and written communication rubric will be utilized in both courses to evaluate both the knowledge conveyed and the communication skill of the presentation.
Apply course material to the application of a real world problems. This includes an appreciation for solving a real world problem and the connection and communication required to accomplish this.	Students will be evaluated on their reflective thinking, ability to gain perspective, making connections, and problem solving through a student reflection, modeled off of the survey and rubric of the CTLE.

VI. Project Safety

Regardless of the work setting, industrial or laboratory, there are potential risks. Ensuring safe work practices is of paramount importance. Operating companies place a strong emphasis on safety by establishing procedures and methods to identify potential risks, developing and implementing risk mitigation plans. Safety training is also an integral part of creating a culture that has safety in mind, first and foremost.

Recently, universities have started to place emphasis on safety and incorporate relevant courses in their degree plans. At the University of Houston-Downtown (UHD), students from the safety management program have the opportunity to work alongside engineering technology students during the design and implementation stages of a senior capstone project. Safety management students benefit from this interaction by getting an opportunity to apply their knowledge and skills to a project that attempts to mimic a “real” life process. Similarly, engineering technology students become aware of methods to assess risks and procedures that must be followed to minimize and mitigate potential risks. In the last ET senior project team we had a Safety Management major so this gave us the opportunity to incorporate safety design into the project.

Regarding the design, construction and operation of the bioreactors, the potential risks were categorized as physical, materials, and engineering hazards. Physical hazards focused on following safe work practices during the construction and/or operation of the bioreactors. Such risks ranged from slips, trips, and falls to manual handling and falling from a height. Material hazards were mainly about construction materials. Access to Material Safety Data Sheets and knowing the potential risks were required of the students. For instance, the Oatley Purple Primer used for the assembly of PVC pipes poses risk of skin, eye, and respiratory irritation. So, proper protective equipment and a well ventilated environment were required for the assembly of PVC pipes. Safety techniques were engineered into the design of the bioreactors. For instance, all wiring was properly insulated to minimize exposure to electrical hazards, especially for the wires used to power the heating element of the bioreactor. In addition, safety management students developed inspection checklists to ensure a safe laboratory and job safety analyses (JSA) were done on a regular basis.

VII. Take Away Messages

This project was designed to bring students from diverse backgrounds together. In the real-world engineers and scientists must continuously communicate, but there is virtually no place for this to happen in the academic setting. This project allowed students from different majors to interact with the goal of creating a system that can evaluate the process of converting plant material to fuel and establish protocols for the created bioreactor systems. Educational advantages of this project include the following:

- Engineering seniors had to create projects that were not only functional, but that met the needs of the biology students. A Safety Management major created additional real-life experience of adding safety protocols to design and building.
- Biology students in an Environmental Microbiology lecture-only course had to do one hands-on component of the class that was then incorporated to an end of semester presentation. The hands-on project allowed opportunities for students to talk with faculty outside the lecture setting.
- Students, faculty and staff in two different departments, Natural Sciences (NS) and Computer Science and Engineering Technology (CSET) had to communicate to coordinate the activities of this project.
- Freshman students doing volunteer activities in the lab were exposed to cross-disciplinary students working collaboratively on a fun project which may encourage them to keep pursuing their degree. This helps improve retention and graduation at UHD. Like many urban universities, UHD has a student population that is ethnically diverse, economically disadvantaged and mostly first ones in their family to go to college. Engagement in high-impact activities with faculty can be critical for keeping students engaged and moving toward graduation.
- Students tackled a cross-disciplinary problem that could be part of sustainable solution in the future. When students graduate they can be the sustainability leaders of tomorrow with knowledge of engineering technology and microbiology.

Acknowledgements

We would like to thank the students of both the Engineering Technology Senior Projects course and the students of the fall 2018 Environmental Microbiology course for their participation in this program. This project overlapped with the initiatives of the UHD Center for Urban Agriculture and Sustainability that is funded by the USDA NIFA grant 2015-38422-24081. This project also received funds from the UHD Center for Teaching and Learning Excellence through a High Impact Practices grant.

References

1. Worldometer.info/world-population, Elaboration of data by United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2019 Revision
2. Sachs, J. 2015. The Age of Sustainable Development. Columbia University Press, New York. 543 p.
3. Bieber, N., Ker, J., Wang, X., Triantafy, C., van Dam, K., Koppelaar, R. and N. Shah. 2018. *Energy Policy*. 113:584-607.
4. Kammen, D. and D. Sunter. 2016. City-integrated renewable energy for urban sustainability. *Science*. 352(6288):922-928.
5. Dixon, R., Scheer, R. and G. Williams. 2011. Sustainable energy investments: contributions of the global environment facility. *Mitig. Strateg. Glob. Change*. 16:83-102.
6. Robak, K. and M. Balcerek. 2018. Review of second generation bioethanol production from residual biomass. *Food Technol Biotechnol*. 56(2):174-187.
7. Bouwma-Gearhart, J. Penny, K. and J. Presley. 2014. Improving postsecondary STEM education: Strategies for successful interdisciplinary collaborations and brokering engagement with education research and theory. J. College Science Teaching. 44(1): 40-47.