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Development of a Biochemical & Biomanufacturing Track in the Unit Operations of Chemical Engineering Laboratory Course

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Development of a Biochemical & Biomanufacturing Track in the Unit Operations of a Chemical Engineering Laboratory Course

Biochemical processes in chemical engineering are widely utilized to produce a variety of products that are used in pharmaceuticals, food processing, biofuel production and many more. A large fraction of recent graduates from chemical engineering programs are seeing increased employment opportunities in the biotechnology and pharmaceutical industries [1]. Hence, it is necessary to train, educate, and expand the knowledge of undergraduate chemical engineering students in the areas of biochemical and bioprocess engineering. One way to achieve this is by integrating biochemical engineering experiments into the undergraduate chemical engineering laboratory curriculum. However, biochemical processes are complex, involving strict handling protocols and long times linked to biological activity to convert raw materials into products. In addition, preparation steps and downstream separations differ significantly from those found in conventional chemical processing.

The Chemical Engineering program at Worcester Polytechnic Institute (WPI) offers a biological concentration for students who choose to focus their studies on biological processes. In addition, to reach a larger percentage of our graduates and to capture the complexity of biochemical processes, a biochemical and biomanufacturing track is now being developed as part of Chemical Engineering's senior level Unit Operations II course (CHE4402). The CHE4402 course, part of the Unit Operations sequence that represents the major laboratory component of the chemical engineering curriculum at WPI, was chosen to implement this track. The goals of this track, which align with ABET outcomes for engineering programs, are to familiarize students with the typical operations of biological processes used in the biochemical industry; to train students to tackle the unique and complex challenges associated with biological systems; and to introduce students to the practical applications and limitations of biochemical engineering models.

The new track introduces three biochemical and biomanufacturing process experiments in two phases. During the first phase, a batch bioreactor is piloted for bacterial fermentation under controlled oxygen concentrations. Students operate the process over the course of two weeks while spending one 4-hour session/week, plus pre- and post-lab work. During the first phase, students assemble the bioreactor, prepare growth media, learn aseptic techniques, and run the batch fermentation experiment to measure substrate utilization, biomass concentration, and acetate production over time. Good manufacturing practice (GMP) is emphasized by mandatory use of batch records and standard operating protocols (SOPs). During the second phase, biochemical and biomanufacturing offerings of CHE4402 will be expanded to include two downstream processes. Examples of new experiments include cell harvesting by continuous centrifugal separation and protein concentration using ultrafiltration followed by column separations for purification. To optimize these student experiences, assessment of student learning outcomes will be performed by evaluating written and oral reports, comparing student assignments from pre- and post-lab work, and conducting a Qualtrics survey. In addition, to help guide the development of the second phase, a separate survey from biochemical companies will be collected and analyzed. It is our expectations at the end of the implementation period that students will have acquired hands-on experience in the operation of biochemical processes and are able to articulate essential steps involved in producing a biochemical product.

Introduction

The integration of a biochemical and biomanufacturing track into the Unit Operations of Chemical Engineering II course (CHE4402) at WPI addresses the growing demand for chemical engineers in the biological and pharmaceutical industries. As these industries continue to expand, they require professionals with specialized knowledge of biological processes and bioreactor systems. Hiring data published by the career development center at WPI [2], showed that 30% of chemical engineering B.S. graduates from 2020–2023 secured positions in the bio-related sector, compared to only two graduates who joined traditional petrochemical employers.

The bio track is being introduced in two phases: The first phase, now successfully completed, was designed to equip students with skills sought by these rapidly growing industries. This phase focused on introducing bioreactor operation, control, and optimization through a dedicated experiment that illustrates key upstream processes. (Bioreactors are culture systems used to produce cells or organisms and are critical for large-scale production of biopharmaceuticals, biofuels, and other biologically derived products.) The second phase, to begin soon, will introduce students to downstream bioprocessing, further strengthening the program's emphasis on bioprocessing and biotechnology. The bioreactor lab experiment enabled students to gain hands-on experience on key aspects of bioprocess engineering, such as assembling the bioreactor, monitoring microbial growth by following substrate utilization, cell formation, and byproduct formation, under carefully controlled conditions, applying aseptic techniques, using batch records, and adhering to standard operating procedures. This paper provides an overview of the course design incorporating the new experiment and an evaluation of its effectiveness in achieving student learning objectives.

The Chemical Engineering program at WPI offers a bioconcentration, but only a small percentage of students choose to specialize in this area. To ensure all students in the program gain exposure to bioprocessing, the newly developed bioreactor lab experiment was introduced in CHE4402. This experiment focuses on batch fermentation of *E. coli* using a bench-scale stirred-tank bioreactor, providing hands-on experience in an area of growing importance in the field. While most students have no prior experience with bioreactors, they are expected to have a foundational understanding of biology, a standard requirement for all chemical engineering students. Additionally, an average of 48.5% of students (based on enrollment data from 2021–2024) take the elective course Introduction to Biological Engineering during their junior year, which further prepares them for this lab. By combining theoretical knowledge with practical experimentation, this unique lab experience bridges the gap between academic preparation and real-world applications, offering students valuable insights into bioprocessing fundamentals [3]. Other academic programs developed biochemical experiments to address similar curriculum and industrial needs. Researchers at Michigan Technological University implemented a semester long batch fermentation experiment to produce L-lysine for the Chemical Engineering Senior Laboratory students [4]. While as, researchers at Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany introduced a one-week lab course in bioprocess engineering for undergraduate students in bioprocess engineering and related disciplines [5].

The purpose of this work is to introduce a carefully designed and integrated bioreactor experiment into an existing lab course, addressing key design challenges to ensure its compatibility with other experiments. This paper details the experiment’s time frame, setup, required protocols, sample results, and outcomes of student learning assessments. Developed

through a rigorous process, this work can serve as a valuable resource for instructors looking to incorporate biochemical experiments into their courses while preparing students for careers in industrial settings.

Objectives

The bioreactor experiment was designed to provide students with a comprehensive understanding of a bioprocess through hands-on experience with real-world applications. A key objective is to familiarize students with biochemical process equipment and the essential steps involved in growing microorganisms while emphasizing safety aspects and aseptic techniques critical to bioreactor operations. Another important objective of the experiment is to emphasize the importance of good manufacturing practices (GMP) by requiring the use of batch records and standard operating procedures (SOPs), a practice widely followed and critical in the industry. Additionally, students examine cell growth by following substrate consumption, acetate production, and cellular concentration over time. They determine key growth parameters such as the maximum specific growth rate (μ_m), doubling time (τ), cell growth yield ($Y_{X/S}$), and apply the Monod equation to predict variations in cellular concentrations over time, comparing predictions with experimental data. Students are expected to scale up their process based on experimental findings, identifying the necessary components and equipment for pilot-scale applications. This task reflects real-world applications, as many industrial processes rely on small scale findings to guide pilot scale operations. The learning objectives for this experiment were developed to align with the objectives of other experiments in the course and were designed to meet ABET requirements.

Design of the Bioreactor Lab Experiment as part of the Unit Operations of Chemical Engineering II Course (CHE4402)

In the standard course offering, self-assigned groups of four conduct three experiments across different areas of chemical engineering over a seven-week term. With the implementation of various tracks, including the bio track, students will select experiments based on their interests. Each experiment runs over two consecutive weeks, with a 4-hour session per week. During the final week, students deliver oral presentations on their first assigned experiments. To support learning and ensure safe experiment operation, students receive lecture notes, process instructions, and a textbook, and must complete lab safety training. Experiments include a catalytic reactor, gas absorber, climbing film evaporator, spray dryer, biodiesel reactor, distillation column, and the newly developed bioreactor experiment. The development and integration of this experiment into the existing course presented several challenges, including time constraints, its interdisciplinary nature, resource availability, fundamental differences from other experiments, and ensuring its level of difficulty is comparable to that of other experiments.

Resource availability, equipment procurement and maintenance, and lab space constraints are major challenges when developing new experiments, especially for pilot-scale engineering labs. Creative solutions are essential, as demonstrated by Rensselaer Polytechnic Institute's Chemical and Biological Engineering Department collaborating with the Biology Department to share space and equipment, enabling the introduction of a biotechnology and bioprocessing course for chemical engineering students [6]. In this study, these challenges were addressed by conducting the experiment at WPI's Biomanufacturing Education and Training Center (BETC), a pilot-scale facility with cutting-edge technology and lab equipment, providing the expertise and resources necessary for the successful design and execution of this experiment.

To optimize time and efficiency, six groups participated, with two groups conducting the experiment simultaneously on each assigned day. Consistent with other experiments, requirements included preparing and submitting a preliminary report, attending a mandatory meeting with the lead instructor before the first session, and completing a formal post-lab report. The lead instructor ensured the requirements matched the difficulty level of other labs and incorporated a design problem to emphasize real-world applications.

Due to the nature of the course and the specific requirements for bacterial continuous growth conditions, assignments were spread out on various days with pre-lab and post-lab requirements ensuring students' active engagement with application-oriented bioprocess as they conducted the bioreactor experiment for the first time. The tasks required during the various days are:

Pre-Laboratory Day

Students work in teams to prepare and submit a preliminary report. In this report, they demonstrate their familiarity with the process equipment, objectives, parameters to be investigated, and propose an experimental plan. They also discuss laboratory safety, addressing chemical, physical, and biological hazards, and perform sample calculations. This assignment helps students become acquainted with the setup and background, preparing them to conduct the experiment effectively.

First Laboratory Day

During this 4-hour lab session, students first attend a 1-hour orientation covering key topics such as bioreactor background, the importance of maintaining sterile conditions, scale-up operations, and laboratory biosafety. Following the orientation, students receive training on the calibration of dissolved oxygen (DO) and pH probes and the use of various equipment. For the remaining time, students work in two teams, each assigned a bioreactor, following strict SOPs they assemble the bioreactor and calibrate the DO and pH sensors, begin completing the batch record, and practice sampling and operation of the analytical equipment.

Pre-the Second-Laboratory Day

A shorter, informal session outside the regular lab schedule, led by the lab manager, TAs, or PLAs, involves autoclaving the bioreactor, preparing and aseptically adding growth media, setting growth parameters, verifying feed control loops, and pre-culturing the bacterial inoculum. Participation is encouraged but optional for students, who are provided with detailed instructions to learn about these steps.

Second-Laboratory Day

During this 4-hour lab session, students work in two teams, carrying out the fermentation process. The fermentation experiment starts with inoculation followed by monitoring bacterial growth by periodically taking samples to determine biomass concentration, substrate utilization, and acetate production, and continuing until the experiment concludes with a dissolved oxygen spike and nutrient depletion. The session ends with bioreactor shutdown and clean-up. Throughout the process, students complete a detailed batch record adhering to SOPs.

Post-Laboratory Day

Students critically evaluate the data, discuss their findings, and prepare the final formal report, addressing the outlined objectives.

Material and Methods

This section outlines the general experimental setup and procedure, based on the methods detailed in [7]. Additional information on required chemicals, solutions, standard operating procedures, and batch record templates is available upon request. A 5 L small-scale fermentation system is used to carry out the fermentation experiment and is schematically shown in Figure 1 [7]. The system consists of the following components: a vessel (Eppendorf BioFLO 120 or 320) filled with the growth medium, a head plate to seal the vessel, integrated feed lines and sensors to monitor and adjust culturing conditions, and an external control system (e.g., pumps and control software) to regulate parameters. This setup allows students to study microbial growth kinetics under controlled conditions of temperature, pH, DO, and agitation. Additional equipment includes an Orion Benchtop pH Meter, Eppendorf 5415C Centrifuge, Cole Parmer LB-200-224e Balance, Cedex Bio Analyzer, Genesys 150 UV-Vis Spectrophotometer, Cole Parmer Masterflex L/S Pump, Sartorius Biosealer TC, and Terumo SCD IIB Welder.

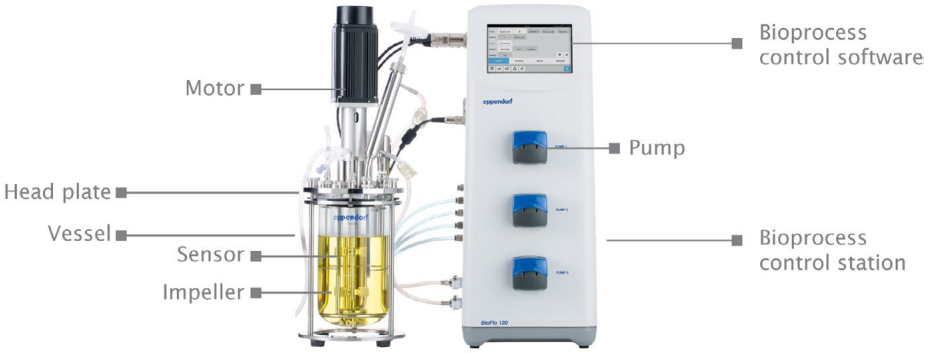

Figure 1: Stirred-tank bioreactor system consisting of bioprocess control station, vessel, and bioprocess control software. The BioFLO 120 bioprocess control station is shown [7].

Bacterial Strain

The bacterial strain used in this study is *E. coli* (ATCC® 25922GFP™) [8], which contains a multicopy vector encoding the green fluorescent protein (GFPmut3) from *Aequorea victoria*. This protein exhibits a green or yellow-green color and fluoresces under UV light (Excitation: 501 nm; Emission: 511 nm). The GFP gene can be isolated and serves as a valuable tool in experiments, such as a nontoxic fluorescent marker or for studying protein interactions [5]. Phase 1 of this study focused on developing and optimizing the batch fermentation experiment using this strain. Protein isolation and production were not included in this phase but will be addressed in phase 2.

Media Preparation

The chemically defined medium is prepared according to [7] and includes the following: 10 X Phosphate Citric Acid Buffer, 240g/L Magnesium Sulfate, 20 g/L Thiamine Solution, 100X

Trace Metal Solution, 70% Glucose Solution, 10% Antifoam Solution, 100mg/ml Ampicillin Solution, and 50% Ammonium Hydroxide Solution.

BioFLO 120 and BioFLO320 Vessels

The bioreactor system consists of a 5 L glass vessel with a 2 L working volume (Eppendorf Inc., Enfield, CT). Two types of bioreactor systems are used: BioFLO 120 and BioFLO 320, which were nearly identical except for differences in the sampling port and heating system. Stirring is achieved using three Rushton-type impellers, and dissolved oxygen (maintained at 30% saturation) is controlled via an oxygen cascade involving regulated flows of air, pure oxygen, and agitation. The temperature is maintained at 37°C, and the pH is kept at 7.0 [7].

pH Calibration and Control

pH sensors are calibrated outside the vessel prior to autoclaving, using a two-point calibration method and standard buffers. The pH is automatically maintained at 7.0 by adding 50 % (v/v) NH_4 OH via a pump using PharMed® tubing between silicone tubing connections. The deadband for pH control is set to 0.05 [7].

DO Calibration and Control

The DO sensor is calibrated inside the vessel using a standard two-point calibration method after sterilization and just before inoculation. In aerobic microbial applications, DO control typically employs a cascade of agitation, airflow, and oxygen flow. By setting a DO cascade, the control station automatically adjusts the process loops to maintain the desired DO level. In this study, the cascade is set to maintain DO at 30% [7].

Tube Welding

Tubing is aseptically connected outside the bioreactor using a tube welder, as shown in Figure 2. The welding process, conducted at temperatures up to 300°C, to ensure sterility. For welding, tubing must be made of weldable material or extended with a weldable connector [7].

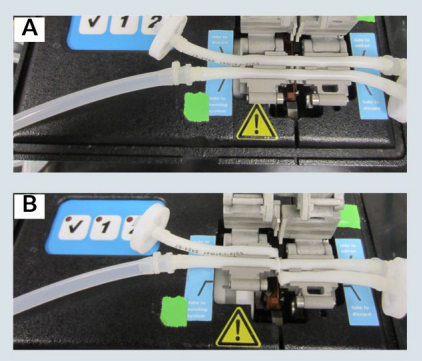

Figure 2: Tube welding. Silicone tubing is extended with weldable connectors made of C-Flex via straight connectors. A: Before welding and B: After welding [7].

Bioreactor Set-up

Assembly of the bioreactor includes installing the pH sensor for pH monitoring and an analog polarographic DO sensor for dissolved oxygen monitoring. The two sensors are installed on the head plate of the bioreactor, through ports, before sterilization of the bioreactor. In addition, the

agitator drive is inserted into the agitator hub on the head plate and the temperature probe is inserted into the Thermowell on the head plate. Other tubes and ports that must be connected and secured include one harvest tube, one sample port, and two ports for overlay liquid addition, one gas inlet with filter, one exhaust with two filters, and one additional exhaust for pressure release during autoclaving [7].

Media Transfer and Inoculum Transfer

Sterile media and inoculum are aseptically transferred to the bioreactor via tube welding. The feed tubes are welded to the bioreactor harvest line and desired volumes transferred using a peristaltic pump.

Optical Density Measurement

After DO sensor calibration and right before inoculation, 20 mL of fresh medium is taken from the bioreactor. One milliliter of medium is used to set blank for measurement of optical density at 600 nm on the Spectrophotometer, and the rest is used to dilute the dense *E. coli* suspension collected in the later phase during fermentation. Samples are taken every 0.5 to 1 hour until a decreasing trend of OD600 is observed [7].

Analysis of Glucose and Acetate using a CedexBio Analyzer

The Cedex Bio photometric absorbance analyzer is used to measure glucose concentrations (0.02–7.5 g/L) and acetate concentrations (0.018–1.4 g/L) by analyzing the absorbance of the selected analytes [7].

Cell wet weight (CWW)

1 ml solution suspension is transferred to a pre-weighed centrifuge tube, separating the *E.coli* cells using the centrifuge, discarding the supernatant, and weighing the pellet-containing tube again. The weight of each pellet is calculated accordingly [7].

Qualtrics Surveys

Qualtrics survey was designed to evaluate student learning in the class and the effectiveness of the newly developed bioreactor experiment. Adapted from the validated Student Assessment of their Learning Gains (SALG) tool (NSF DUE 0920801), the survey prompts students to retrospectively evaluate their growth toward each student learning objective and assess the impact of various learning activities on their learning gains. To ensure a more specified assessment, the survey was modified to incorporate course specific learning activities and targeted questions related to the bioreactor experiment. It was administered to both bioreactor lab participants and the entire class. Additionally, a separate survey was distributed to industry professionals to guide the development of phase two, ensuring alignment with current industrial needs.

Theory

Substrate consumption, acetate production, and cellular concentration were followed as a function of time during the experiment and were used to determine cell growth and kinetics parameters including the substrate consumption (g/L), acetate production (mmol/L), and cellular concentration (g/L) with time, the maximum specific growth rate μm (hr^{-1}), the doubling time τ (hr), and the cell growth yield $Y_{X/S}$. Some groups attempted to use the Monod equation to predict

the variation of concentrations with time, comparing them with experimentally measured values. The specific growth rate is represented by μ, and expressed as:

$$\mu = \frac{1}{X}\frac{dX}{dt} \qquad (1)$$

Where X is the concentration of cells in the medium (g/L). Biomass concentration was measured using optical density at 600 nm. To convert optical density to biomass concentration (g/L), a standard curve between optical density and cellular wet weight (CWW) was established and applied.

If the processing of substrate is assumed to be controlled by a single enzyme system and the substrate concentration is limited, μ can be modelled with Michaelis-Menten kinetics using the Monod Equation 2.

$$\mu = \frac{\mu_m S}{K_s + S} \qquad (2)$$

where μ_m is the maximum specific growth rate constant (hr^{-1}), S is the substrate concentration (g/L), and K_s is the half saturation constant (g/L) which is equal to S when $\mu = 1/2\mu_m$. At the start of the fermentation, $S >> K_s$, and therefore $\mu = \mu_m$ in Equation 2. The solution to Equation 1 for exponential growth is shown in Equation 3 [4].

$$ln\left(\frac{X}{X_0}\right) = \mu_m t \qquad (3)$$

where X_0 is the initial biomass concentration in the medium (g/L). Another important parameter is the doubling time (τ), the time required during the exponential growth phase for the concentration of cells to double. Based on the above equation, when $\frac{X}{X_0} = 2$, the doubling time is equal to:

$$\tau = \frac{ln(2)}{\mu_m} \qquad (4)$$

The cell growth yield ($Y_{X/S}$) is a measure of the change in cell concentration per amount of substrate consumed. The value of the growth yield is typically 0.4-0.6 g dry cells/g substrate consumed [10]. The cell growth yield ($Y_{X/S}$) is expressed as:

$$Y_{X/S} = \frac{-\Delta X}{\Delta S} \qquad (5)$$

and it was determined in the experiment by calculating the cellular concentration and substrate concentration at two given times.

Scale-up

Bioprocess development typically begins at the bench scale, optimizing scale-independent parameters like growth conditions and media composition. Scaling up to production-scale bioreactors introduces complexities, and without careful planning, significant variations in cell growth can occur [9]. In this experiment, students used their results of *E. coli* fermentation and demonstrated the scale-up capabilities of the bench scale fermentation system to the pilot scale considering critical scalability-related engineering parameters. Parameters that were considered include proportional vessel/ impeller geometry, gas flow rate (SLPM), impeller power numbers

(Np), impeller power consumption per volume (P/V), and agitation speed (rpm). The scale up vessel would have a volume of 100 L and an inner diameter of 380 mm, and the scale-up approach follows a constant P/V strategy. The impeller power consumption per liquid volume (P/V, W/m^3) can be calculated using the following equation [9]:

$$P/V = \frac{N_p \times \rho \times N^3 \times d^5}{V} \quad (6)$$

N_p: Impeller Power Number, a dimensionless number associated with different type of impellers, ρ: DI water density = 1,000 kg/m³, N: Agitation speed (rps), d: Impeller outer diameter (m), and V: Full working volume (m³).

Results and Discussion

Microbial Growth Results

Figure 3 illustrates a typical growth curve from one team and a single-day experiment, showing substrate (glucose) consumption and biomass production, while Figure 4 shows acetate accumulation as a byproduct. The results show glucose depletion over time, with biomass production characterized by a lag phase followed by an exponential growth phase, as the experiment lasted only 5.5 hours and did not reach later phases. Acetate accumulation was controlled and maintained at low concentrations in most experiments. However, one team experienced uncontrolled acetate accumulation, which affected substrate and biomass concentrations. Excess acetate, toxic to cells, disruptive to their growth, leading to lower glucose consumption and further acetate production. This highlighted the importance of controlling growth parameters, with potential issues attributed to a malfunctioning DO probe or pH fluctuations. Results from other teams were consistent with the expected trends.

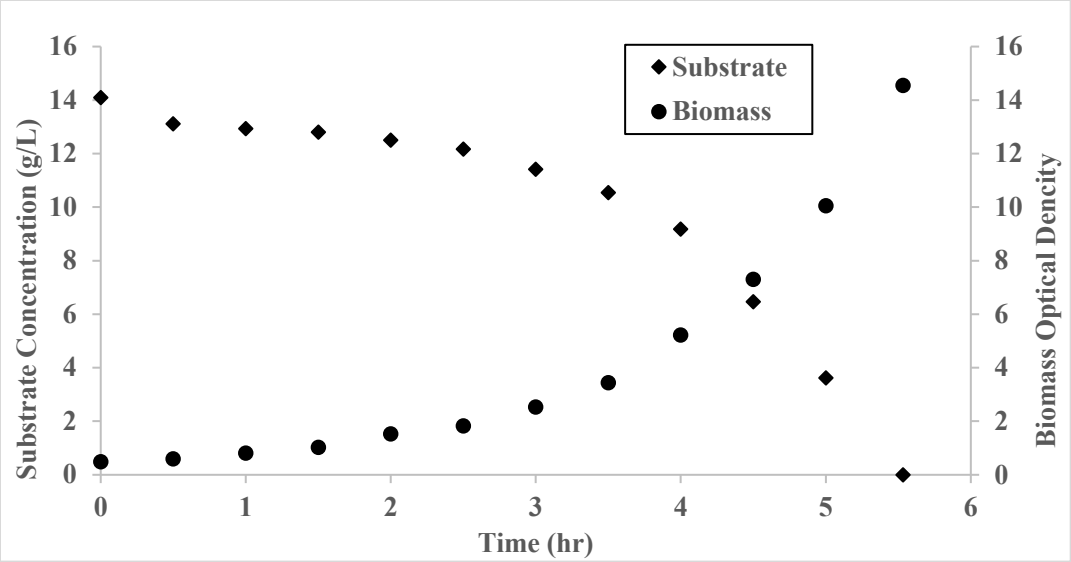

Figure 3: Representative growth curve from a single-day experiment showing substrate consumption and biomass production over time

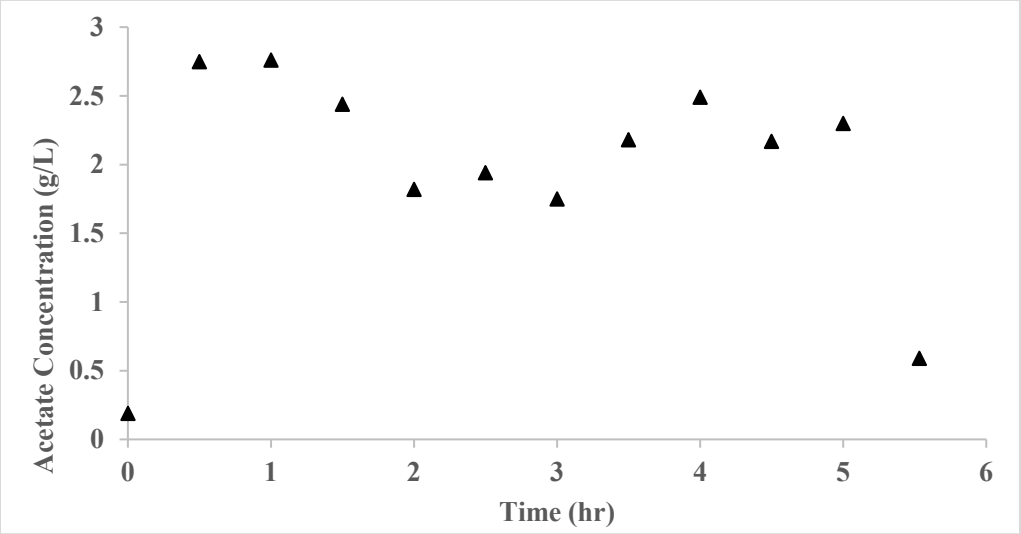

Figure 4: Representative curve of acetate accumulation over time from a single-day experiment.

Results of cell growth parameters from all teams conducting the fermentation experiment under similar conditions are shown in Table 1. Table 1 shows that cell growth parameters were consistent across all teams except Team 3. As previously discussed, uncontrolled acetate accumulation in Team 3's experiment resulted in variable environmental conditions compared to the other experiments. Excluding Team 3, the average maximum specific growth rate (μ_{max}) was calculated as 0.33 ± 0.02 hr^{-1}, reflecting the fastest microbial growth rate under optimal conditions. The average doubling time was 2.10 ± 0.15 hr, which is slower than the typical doubling time for bacteria under aerobic conditions (20–30 minutes) [10] but may vary depending on the specific strain. The average yield coefficient was 3.22 ± 0.70 g biomass/g substrate, significantly higher than the typical aerobic range of 0.4–0.6 g biomass/g substrate [10]. This higher yield is likely due to the use of CWW to correlate optical density (OD) with cell concentration. Wet weight measurements can include extracellular water and other

components, potentially overestimating actual biomass. This discrepancy will be further investigated to refine the methodology and enhance the accuracy of growth yield measurements. Additionally, results from kinetic modeling using the Monod equation and scale-up calculations were inconclusive and will be studied further to improve the experiment's reliability.

Table 1: Summary of cell growth parameters from all teams with average values calculated excluding values from Team 3.

Team	Initial Glucose Concentration g/L	μ_{max} hr^{-1}	τ hr	Yield $g_{biomass}/g_{substrate}$
1	-	0.30	2.32	2.51
2	14.15	0.35	1.96	4.26
3	**14.57**	**0.14**	**4.86**	**0.36**
4	14.73	0.31	2.23	2.59
5	14.09	0.34	2.05	2.95
6	15.39	0.35	1.96	3.82
Average	14.59±0.53	0.33±0.02	2.10±0.15	3.22±0.70

Assessment of Student Learning and the Effectiveness of the New Experiment

Various qualitative assessments were used to evaluate students' work and assess their achievement of learning objectives including reviewing pre-lab reports, formal post-lab reports, and oral presentations. The review demonstrated that students became more familiar with bioreactor operations, developed a solid understanding of conducting batch fermentation experiments, and were able to effectively analyze the results and produce professional written reports and oral presentations. While direct comparisons between pre-lab and post-lab reports were inconclusive due to their focus on different aspects of the experiment, notable progress was evident in the methodology section, as students had no prior experience with bioreactors before the lab. One student remarked, *"I learned about how bioreactors work and are operated. Using that knowledge is something I will be looking to pursue in a job."*

Additionally, a Qualtrics survey was administered anonymously to students during the final week of the term to quantitatively evaluate their achievement of learning outcomes and gather feedback on the effectiveness of the newly developed bioreactor experiment. Participation in the Qualtrics survey was very strong, with 44 out of 52 students in the class responding. The survey targeted two groups: students who conducted the new bioreactor experiment ($n_{bioexperiment}$ = 23) and the entire class (n_{class} =44), including those who did not participate directly. It collected feedback on key aspects in class such as understanding of main concepts, gains in skill development, engagement level, difficulty level, the usefulness of learning activities, and overall satisfaction. By comparing responses between the two groups, the survey provided insights into the effectiveness and impact of the new bioreactor experiment and highlighted areas for potential improvement in its design and implementation.

A main area of the survey assessed students' gain in understanding the following: The main concepts explored in class, The relationships between the main concepts, How ideas from this class relate to ideas you encounter in other classes, and How studying this subject area helps people address real world issues. Response options ranged from "no gain" to "great gain." The

results (n_{class} =44) showed that the highest gains were reported in the category " How studying this subject area helps people address real world issues," with 41% of students selecting this category. Across all categories, "good gain" was the most frequently chosen response. These data indicate that the class effectively helped students connect the subject matter to real-world applications and that the course content and teaching approach successfully emphasized practical relevance. One student commented about the connection between the new bioreactor experiment and industry, "*As I am highly interested in biofermentation research the bioreactor lab was highly helpful for its use of GMP adjacent practices and hands on opportunity*." Additionally, the majority selecting "good gain" across all categories reflects a generally positive learning experience, with room for further enhancement to achieve even higher levels of understanding and engagement in specific areas.

Data collected from the survey assessing students' success in meeting key learning objectives is shown in Table 2. Response options ranged from "no gain" to "great gain." The main findings suggest that students gained the most in "Collect, analyze, & present data from laboratory & process equipment" category which had 64% of students reporting "great gain" and 23% of students reporting "good gain." On the other hand, the lowest percentage of "great gain" responses were identified in the "Design & plan a safe and efficient experiment" and "Deliver clear, concise, organized, & professional oral technical reports" categories, suggesting the need for additional support or instruction to improve their ability to achieve these learning objectives. Overall, most responses were in the "good gain" or "great gain" categories, indicating a strong alignment with the course's learning objectives and a solid understanding of the key concepts.

Table 2: Data evaluating students' improvement in understanding key learning objectives. The results presented are from the entire class (n = 44).

Survey Item	No gains	A little gain	Moderate gain	Good gain	Great gain
Design & plan a safe & efficient experiment	0%	5%	21%	46%	30%
Collect, analyze, & present data from laboratory & process equipment	0%	2%	11%	23%	64%
Compare experimental data & results to expected values from the literature & discuss the results	0%	7%	7%	48%	39%
Prepare & deliver clear, concise, organized, & professional written technical reports	0%	2%	2%	43%	52%
Prepare & deliver clear, concise, organized, & professional oral reports	0%	5%	23%	43%	30%
Practice effective group dynamics to work as a member of a team	0%	9%	16%	32%	43%
Apply safe laboratory practices important in the chemical industry	0%	9%	9%	43%	39%

Data collected from surveying students who participated in the bioreactor lab experiment ($n_{bioexperiment} = 23$) about their experience in this lab compared to other unit operations labs is shown in Table 3. Response options ranged from “a lot less than other labs” to “a lot more than other labs.” As shown in Table 3, the bioreactor lab stands out as one of the most impactful labs in terms of learning, with 91% of students reporting greater learning compared to other labs and 69% indicating higher enjoyment. This demonstrates its strong educational impact and engaging design. One student commented, *“The bioreactor was the most interesting and fun to operate and understand.”* In the challenge level category, most students rated the lab as moderately challenging (48%) or more challenging than other labs (31%), reflecting a well-balanced experimental design. However, a notable 22% found it less challenging, suggesting opportunities to introduce more complex or problem-solving tasks. Effort levels were moderate to high, with 47% putting in more effort than other labs, though 39% reported effort "about the same." Overall, the results indicate that the bioreactor lab outperforms other labs in learning and enjoyment and should serve as a model for designing or revising other labs in the course.

However, incorporating advanced challenges and ensuring consistent engagement across all students could further enhance its impact.

Table 3: Comparison between the bioreactor lab and other unit operations labs, in terms of students' learning, enjoyment, content challenge, and effort. Results presented are from students who participated in the bioreactor lab experiment (n=23).

	Frequency				
Survey Item	**A lot less than other labs**	**A little less than other labs**	**About the same as other labs**	**A little more than other labs**	**A lot more than other labs**
How much did you learn from the FERMENTATION/ BIOREACTOR lab experience?	0%	9%	0%	48%	43%
How much did you enjoy the FERMENTATION/BIOREACTOR lab experience?	0%	13%	17%	26%	43%
How challenging was the FERMENTATION/BIOREACTOR lab experience?	13%	9%	48%	22%	9%
How much effort did you put into the FERMENTATION/BIOREACTOR lab experience?	4%	9%	39%	30%	17%

Additionally, when the same group of students ($n_{bioexperiment} = 23$) were surveyed about their understanding of biochemical processes and bioreactors after completing the lab, the results showed that 48% of the students reported a great gain and 39% reported a good gain and when asked about the lab's impact on their aspirations for further education or a career in the biochemical field, 4% reported a great impact, and 22% reported a good impact. The findings show that the bioreactor lab experiment effectively enhanced students' understanding of biochemical processes and bioreactors, likely due to its hands-on and practical approach. However, the relatively low percentages of students reporting a "great gain" or "good gain" in aspirations for further education or careers in the biochemical field suggest that the current structure may have limited influence on long-term career or academic goals and highlights opportunities for improvement.

Data collected from a comparative survey question targeting students who participated in the bioreactor lab experiment ($n_{bioexperiment} = 23$) and those who did not ($n_{remaining} = 21$) explored how helpful various learning activities were for students' learning is shown in Figure 5 and Figure 6, respectively. Response options ranged from "No help" to "Great help." Figure 5 and Figure 6 show that both groups agreed that conducting the experiment was the most important activity for their learning, highlighting the value of hands-on experiences. However, the two surveyed

groups differed in their responses in terms of which learning activities were highly rated as providing "much help" or "great help" to their learning. Students in the bioreactor lab relied more heavily on the experiment advisor, with 68% rating this activity as the second most helpful, while students in the traditional labs relied more on their team members, with 77% ranking this activity as the second most helpful. This difference suggests that the interdisciplinary nature of the bioreactor lab introduces new content, methods, and skills that may limit the ability of students to support each other effectively.

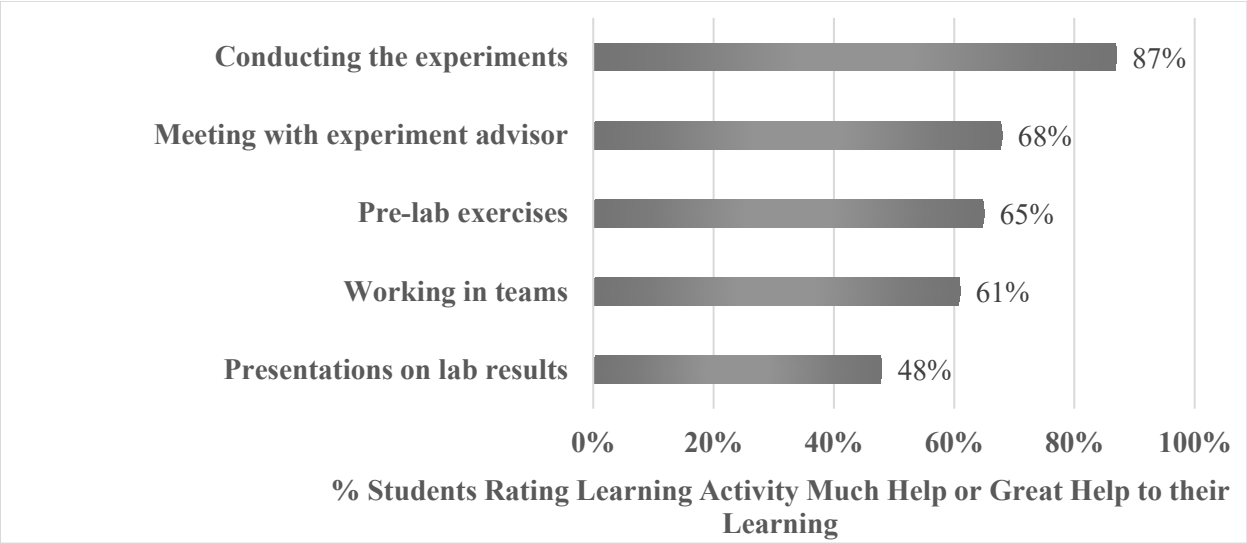

Figure 5: Students' rating of learning activities that provided them with much help or great help. Results presented are from students who participated in the bioreactor lab experiment (n=23).

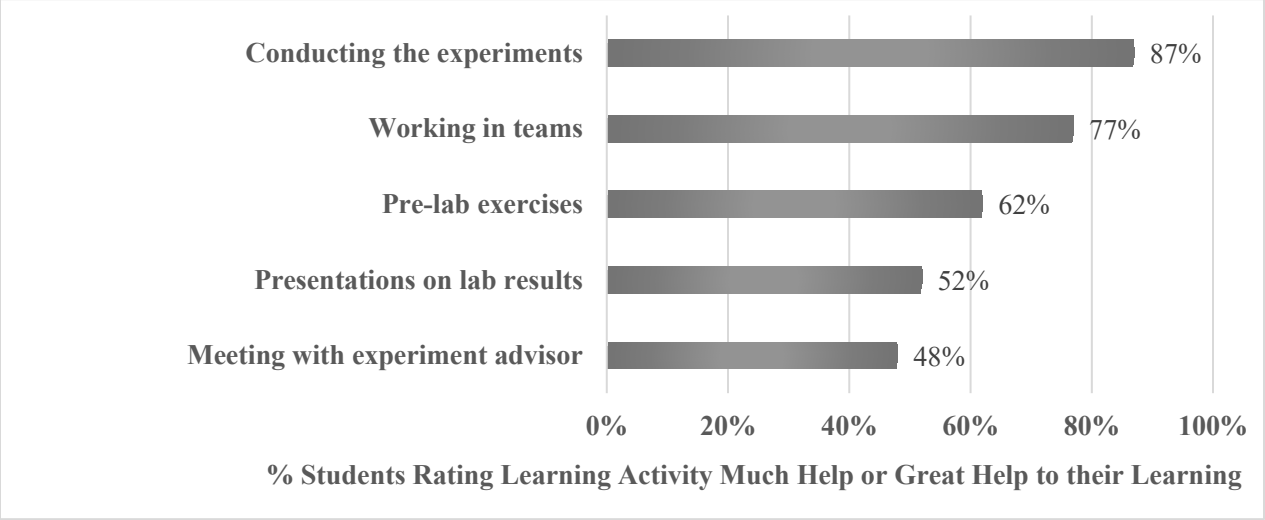

Figure 6: Students' rating of learning activities that provided them with much help or great help. Results presented are from students who did not participate in the bioreactor lab experiment (n=21).

Conclusion

The implementation of the new bioreactor lab experiment was successful and met the intended learning objectives, effectively addressing a critical need in the curriculum. The growth parameter results demonstrated the experiment's validity and relevance, with scalability and modeling identified as areas for further development. Feedback from the Qualtrics survey highlighted strong student gains in achieving learning objectives and understanding key concepts, stressing the lab's educational impact and engaging design. Comparative analysis confirmed the lab's alignment with broader course goals while emphasizing the importance of aligning the lab more closely with industry demands, reinforcing the need for a specialized bioprocessing track.

Throughout the course, students were consistently exposed to standard industrial protocols and safety practices, ensuring technical proficiency and professional readiness. This work provides a framework for integrating hands-on, industry-relevant experiences into curricula, bridging the gap between academic preparation and real-world applications. Future efforts will focus on incorporating more complex problem-solving challenges, improving scalability and modeling aspects, and moving forward with phase two of the work incorporating insights from an industry employee survey to better meet workforce expectations. These efforts aim to further inspire students and connect their learning experience to career opportunities, though the positive impact of this initiative is already evident.

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