

# A REMOTE, HANDS-ON, AND LOW COST SOURDOUGH LAB FOR FIRST-YEAR CHEMICAL ENGINEERING STUDENTS

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## INTRODUCTION

Due to COVID-19, courses at our university were held online in Fall 2020, which included our lab-based first-year chemical engineering experience. The context of the term led to many difficulties in the administration of this hands-on experience, where students were no longer co-located – distributed across four continents and ten time zones – and unable to access equipment or materials we typically kept in a lab space on campus. Instead, we had to design experiments that our students could run safely at home, with materials that they may already have on hand or would be able to source locally. Altogether, this led to a significant amount of variability based on student locale and context as well as the challenge of running an experience that was both remote and hands-on, seemingly a contradiction.

We adapted to the online conditions by embracing the contradiction of a remote, hands-on lab that accepted the variability inherent in students conducting experiments at home. The desired learning outcomes for the lab were (1) model a chemical process using material balance, thermodynamic, and kinetics concepts, and (2) describe how chemical engineers design and troubleshoot experiments. Drawing on a hobby that had become more popular during COVID lockdowns, we developed a remote-lab experience where first-year students grew and analyzed the activity of sourdough. This hands-on activity was selected for a six-week at-home lab due to its low cost and non-hazardous materials. Students were encouraged to use whatever starch, flour, or sugar sources they had on-hand, access widely available equipment found in homes (e.g., plastic bottles, balloons, rulers, and kitchen measuring devices), and carry out the procedures safely in a non-laboratory setting (e.g., a residential kitchen or bathroom). Personal expenditures by students were expected to be no more than \$5 in order to participate fully, most commonly spent on balloons and baker's yeast. Since Fall 2022, most materials necessary for participating in these experiments are distributed by the department (i.e., flour, balloons, containers, and baker's yeast, totaling ~\$70 for the materials shipped from Amazon for 12 students,

with excess materials stored by the department for future use). The only materials students need to provide currently are water and plastic or glass bottles.

In this paper we describe the design of this six-week hands-on module for first-year engineering students that was developed during the COVID lockdowns. We share our protocols and lessons learned from the development of this course, along with data to support student learning and positive student experiences. We will also discuss why we have continued to run this sourdough experiment as we have transitioned back to in-person teaching, and the new challenges that have arisen.

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## Pedagogical Background and Class Context

Since the early 2000s, chemistry educators have begun to explore inquiry-based, open-ended laboratory experiments in place of standard “cookbook” experiments as a method to promote undergraduate engagement and curiosity.<sup>[1, 2]</sup> Over the course of the past decade, chemical engineering educators have more widely begun to implement the inquiry-based learning pedagogy as a way to provide hands-on chemical engineering experiences to undergraduate students.<sup>[3-5]</sup> This has resulted in greater understanding of core chemical engineering problems in thermodynamics, transport, and kinetics.<sup>[5, 6]</sup> During the COVID-19 pandemic, many institutions were forced to develop asynchronous and hybrid learning curricula to substitute for in-person experiences.<sup>[6, 7]</sup> For example, educators at Rice University were able to incorporate the study of enzyme kinetics in an asynchronous format.<sup>[6]</sup> However, these methods required distribution of specific enzymes and equipment, whereas we provide a simple and cost-effective alternative to allow undergraduate students to conduct enzyme kinetic studies at home.

Laboratories that involve fermentation are also not new in helping students learn chemical concepts. For example, beer brewing has previously been used as teaching tool for general chemistry,<sup>[8]</sup> biochemistry,<sup>[9, 10]</sup> and as an analytical lens for the entirety of the chemical engineering curriculum.<sup>[11]</sup> Similarly, baker’s yeast experiments have also been conducted for educational purposes on biosynthesis<sup>[12, 13]</sup> and fermentation kinetics.<sup>[14-16]</sup> Connecting tangible, hands-on experiences with chemical engineering concepts through such pilot-scale experiments facilitates understanding and prepares students for real-world engineering work.<sup>[17]</sup>

Although experimental procedures using commercially available baker’s yeast for education purposes have been well documented, procedures to measure strain kinetics using student-specific home sourdough cultures have not yet been published. Existing baker’s yeast experiments use water displacement as a means to measure CO<sub>2</sub> production.<sup>[14, 15]</sup> The published experimental setups require tubing and glassware, which would have been prohibitively expensive to ship to students, especially given that a quarter of our students were residing internationally during the first instance of this experimental module. Additionally, as far as the authors are aware, utilizing these protocols as a basis for a course-based undergraduate research experience, or for inquiry-based experimental design, has not been reported.

This laboratory experience sits within a first-year one-semester course for students, The Art of Engineering, that students are required to take in the fall or spring. Students in this course are introduced to all engineering majors, discuss future career pathways, and engage in a rapid prototyping and design project. Every student must participate in a departmental project, taught to expose students to the ways of thinking and doing in the engineering discipline.

However, since students are encouraged to participate in a departmental module other than their anticipated major, these projects are often the only contact point for students with the discipline and cannot be relied upon as background for future courses in the chemical engineering curriculum.

## Selection of Sourdough as a Pedagogical Tool

During the COVID-19 pandemic, there was a major growth in interest in sourdough culturing at home, driven by shortages of baker’s yeast (*Saccharomyces cerevisiae*, also sold as brewer’s yeast) in supermarkets during the spring of 2020.<sup>[18, 19]</sup> Commercial yeasts catalyze the reaction to convert the starch in flour to amylose via amylase,<sup>[20]</sup> then to maltose and glucose sugars ( $C_6H_{10}O_5$ )<sub>n</sub> + nH<sub>2</sub>O → nC<sub>6</sub>H<sub>12</sub>O<sub>6</sub>.<sup>[21]</sup> One yeast metabolic process, alcoholic fermentation, converts sugars to ethanol and carbon dioxide  $nC_6H_{12}O_6 \rightarrow nCO_2 + nC_2H_5OH + nC_3H_6O_3$ ,<sup>[22]</sup> that allows the bread to rise and form its crumb (the air pockets in bread).

Sourdough, unlike baker’s yeast, is a mixed culture primarily composed of lactic acid bacteria (genus *Lactobacillus*)<sup>[23]</sup> and wild acid-tolerant yeasts (most commonly *Kazachstania humilis* and *Saccharomyces* sp.)<sup>[24, 25]</sup> that can be used to leaven breads and other baked goods.<sup>[26]</sup> Dozens of species of lactic acid bacteria have been isolated from sourdough cultures; most famously, *Lactobacillus sanfranciscensis* is thought to give San Francisco sourdough bread its distinctive taste.<sup>[23, 27-29]</sup> Lactic acid fermentation can follow a homolactic fermentation (producing two molecules of lactic acid,  $nC_6H_{12}O_6 \rightarrow 2nC_3H_6O_3$ ) or heterolactic fermentation (producing lactic acid, carbon dioxide, and ethanol,  $nC_6H_{12}O_6 \rightarrow nCO_2 + nC_2H_5OH + nC_3H_6O_3$ ).<sup>[30]</sup> Sourdough starters have been used to teach experimental approaches such as high-throughput microbiome sequencing techniques.<sup>[31]</sup>

CO<sub>2</sub> production of a sourdough starter follows much slower kinetics – in part because of the heterogeneous products and pathways<sup>[32]</sup> – resulting in rise times that are much longer for sourdough loaves than for breads leavened with commercial baker’s yeast,<sup>[33]</sup> which have been engineered to minimize rise time.<sup>[34]</sup> The longer rise time allows for greater flavor development, resulting in sourdough bread’s more complex profile.<sup>[35]</sup> The kinetic features of sourdough starter made it an interesting system for students to explore, where students are able to contrast the behavior of highly engineered commercially available yeasts with wild yeasts. By doing so, home-cultured sourdough colonies would provide students insight into microbial growth conditions in batch bioreactors, while maintaining an authentic undergraduate laboratory experience at home with a safe, low-resource introduction to engineering principles. Additionally, leveraging the already present interest in growing sourdough starters in Fall 2020 presented an opportunity for our project to be more relevant and meaningful to students compared to previous projects we had offered to students in the past.

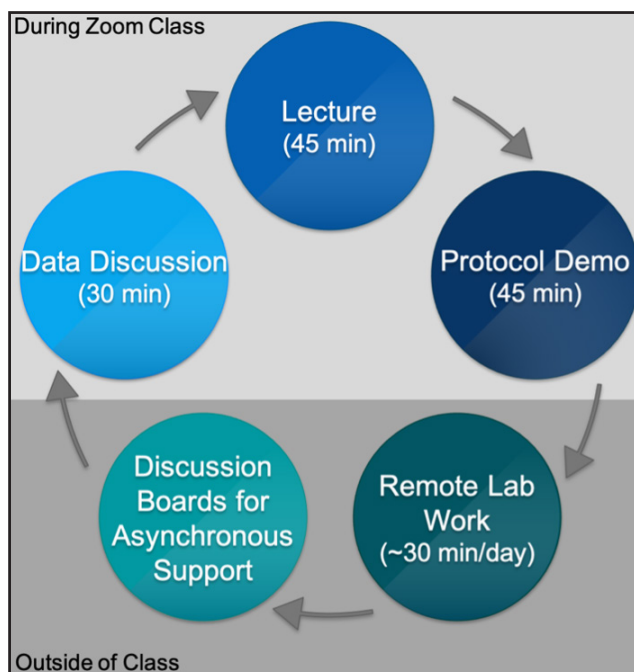
## LEARNING ACTIVITY DESIGN

Students engaged in guided inquiry<sup>[36]</sup> throughout the six weeks, where students were given background and protocols for quantifying sourdough starter performance. Following these protocols allowed students to grow the symbiotic bacteria-yeast cultures that were highly dependent on their materials and environment and led to a situation in which neither the instructors nor the students could predict the activities of the resulting sourdough starters. Embracing an inquiry-based model was chosen to help make the variability students encounter feel more authentic, which has been associated with student learning gains in STEM,<sup>[37]</sup> even when done online.<sup>[38]</sup> To support students' inquiry, synchronous meetings (held for two hours via Zoom) focused primarily on introducing students to new protocols they could use to further investigate their starters (45 minute demonstration), introducing how to model and measure metabolic reactions and the kinetics of cell growth (45 minute lecture), and engaging with data and experimental troubleshooting through a chemical engineering lens (30 minute discussion). Decoupling the laboratory time from class meetings also allowed students to try as many conditions as they wished and to make as many attempts as they wanted. Students were expected to run their experiments remotely (5-30 min/day outside of class) and access asynchronous support as needed (via discussion boards and recorded protocol demonstrations). A visual representation of this breakdown of in-class and out-of-class activities can be seen in Figure 1.

Each of the first five weeks introduced a new protocol to students matched with a chemical engineering concept, as shown in Table 1. Each week built on the concepts and experiments of weeks prior. In Week 6, as a capstone to experiments, students pitched the use of their team's selected sourdough starter for use by a commercial baked goods company. As a note, we have typically scheduled these six weeks of class time to run across fall or spring breaks (typically between weeks 4 and 5) to give students additional time for culturing.

We decided to use exclusively household items in our experiment and to provide funds to students to purchase essential items for the experiments if they did not have access to them at home. Materials were expected to cost no more than \$5 per student. All but two students had access to all materials in Fall 2020; two students requested balloons, which were purchased and shipped to students using Amazon. Students universally had access to conventional US volumetric measurements (cups, tablespoons, and teaspoons), so measurements are given using those units instead of in metric.

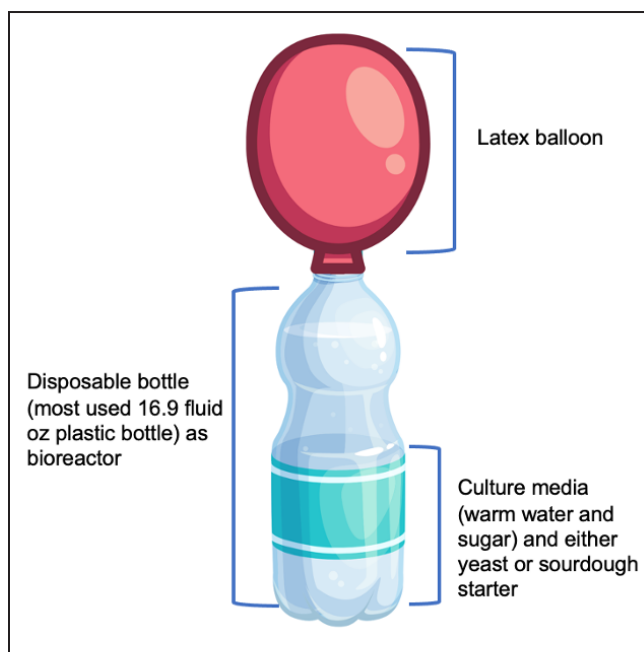
As standard laboratory equipment was unavailable to students outside of our classroom, we advised on a few workarounds that would make the experiments manageable



*Figure 1. Breakdown of how synchronous and asynchronous class time was spent during this unit.*

Week #	Experiment Introduced	Chemical Engineering Content
1	Sourdough Culturing	Overview of Bioengineering and Metabolic Engineering
2	Determination of CO <sub>2</sub> Conversion from Carbohydrates	Introduction to Material Balances
3	Measuring CO <sub>2</sub> Evolution Kinetics	Introduction to Reactor Design and Reaction Kinetics
4	Optimization of Reaction Rate Based on Substrate (Sugar) Concentration	Experimental Design and Optimization
5	Modeling Carbohydrate Oxidation and Cell Growth Kinetics	Modeling Reaction Kinetics, Monod Growth Kinetics
6	Final Pitch Presentations	

at home. Namely, we provided a way for students to estimate carbon dioxide production using a balloon and measuring tape. Students could obtain water between 30–40 °C without a thermometer by mixing 35 vol% ice water with boiling water, as Baker’s yeast optimally grows at 35 °C, and its kinetics are highly dependent on temperature – below 30 °C and above 40 °C, yeast growth rates sharply fall off.<sup>[39]</sup> (As an aside, these simple measurements provide an opportunity to discuss with students the effects of measurement approaches on precision and accuracy, some suggestions for which are included in the Appendix.) Laboratory bioreactors were replaced with plastic bottles capped with balloons, a schematic of which is shown in Figure 2. All guidance given to students to enable safe, home manipulations for these experiments can be found in the protocols distributed to students (with metric units provided for ease of use by other instructors), which can be obtained by contacting the corresponding author at [chen.christopher@columbia.edu](mailto:chen.christopher@columbia.edu).



**Figure 2.** Schematic of at home experimental setup to measure carbon dioxide output of sourdough cultures.

### Laboratory Protocols

In the first week of class, we introduced students to chemical engineering and broader applications of metabolic engineering. Initial culturing procedures were provided to students, who were encouraged to make one standard wheat flour sourdough culture, based on the Wild Sourdough protocol from the Sourdough for Science Project.<sup>[40]</sup> This culture was made by combining equal parts wheat flour and water in a container and leaving it covered with a cloth for a week. Students were given the choice to introduce other

variables into a second culture (e.g., introducing different substrates, inoculating with yeasts found on fruits, adding inhibitors like salt, placing in different temperature environments). As students needed an initial inoculum for further weeks of the remote lab, getting students started as early as possible was very important so that remote troubleshooting could be conducted, if needed.

The second week of experiments involved comparing carbon dioxide production of two samples of flour-grown sourdough cultures, where one was fed a bolus of sucrose (table sugar) and the other was not. Because the sourdough bacteria and yeasts cannot be separated from the flour-based culture media, preparing a control without sucrose can account for growth on the flour media. This experiment demonstrated principles of mass conservation in a closed system using balloons to measure the moles of carbon dioxide produced (Figure 3). Students were asked to analyze why carbon dioxide yields were much lower in biological metabolism than in a sucrose combustion reaction.

During the third week, we introduced the stages of cell growth and how yeast cells utilize substrate over time.<sup>[41]</sup> Carbon dioxide production was used as a proxy for the number of cells present in the culture. Students prepared two culture samples with identical sucrose media, one inoculated with sourdough starter and one inoculated with commercial yeast (Figure 4). Students were asked to compare growth rates of commercial yeast and sourdough culture and draw conclusions about sourdough bread’s commercial viability.

The fourth week of class involved design of experiments where students were asked to vary initial sucrose concentration to determine the optimal starting conditions for maximum growth rate of their cultures and a commercial yeast culture. Using the same setup, students were tasked to conduct these experiments with at least three different initial substrate concentrations (of their choice) with both the sourdough and commercial yeast cultures against controls that contained no added sugar. Carbon dioxide production measurements were taken over time and plotted to find growth rates using a Microsoft Excel<sup>®</sup> template provided to students. Figure 5 shows an example of the Excel template used to determine the growth rate of a sourdough culture experiment.

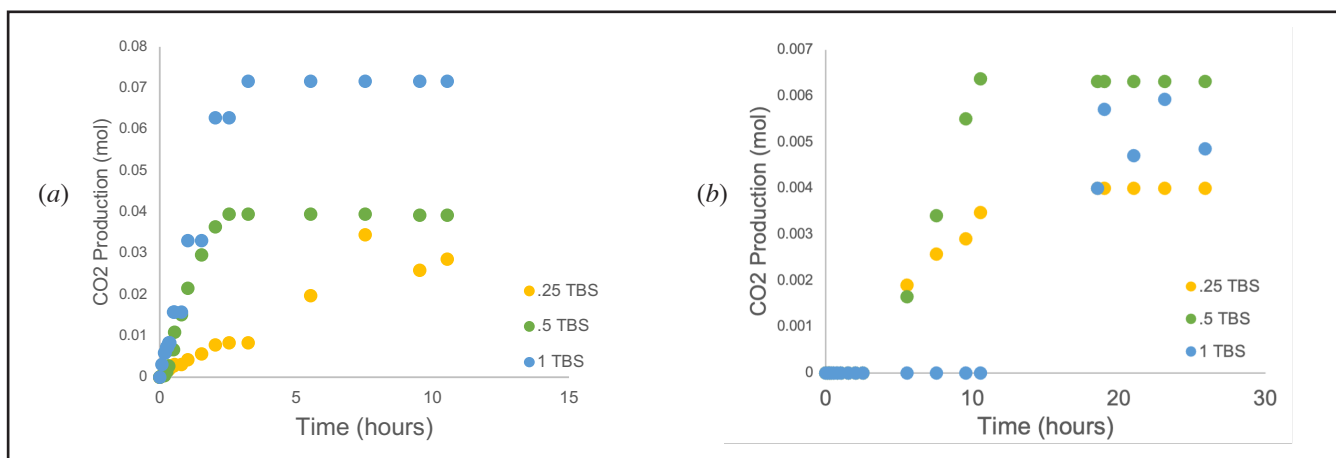
The fifth week of class was spent going over Excel analysis techniques and pitch presentation guidelines. Monod growth kinetics<sup>[42]</sup> were assumed, following the equation

$$\mu = \frac{d[P]}{dt} = \frac{\mu_{max}[S]}{K_s + [S]} \quad (1)$$

where  $\mu$  is the growth rate,  $\mu_{max}$  is the maximum reaction velocity,  $[P]$  is the product concentration,  $[S]$  is the initial substrate concentration, and  $K_s$  is the substrate concentration when the reaction rate is one-half of  $\mu_{max}$ . Using an



**Figure 3.** Photographs of experiments comparing the carbon dioxide outputs of unfed sourdough and sourdough fed with sugar. Right bottle: sourdough fed with 1 teaspoon of sugar. Left bottle: not fed. Timepoints taken at 0, 6, and 22 hours (from left to right in the figure). Students used measurements from these experiments to determine that their sourdough culture had a 1.68% yield on sucrose fed using material balances.



**Figure 4.** Sample student plots of  $\text{CO}_2$  production versus time for (a) commercial Baker's yeast (Fleishmann's yeast) and (b) sourdough culture at various sugar concentrations. Lag phase for the sourdough culture is seen to be much longer than those for commercial Baker's yeast. Decreased carbon dioxide production of the 1 tablespoon (TBS) sample is likely due to substrate inhibition of this particular sourdough starter. 1 tablespoon in sugar is approximately 15 g.

Excel template provided to students that described the steps to analytically calculate  $\mu_{max}$  and  $K_s$  using a least-squares parameter fitting (Figure 6), students could input their data and make the necessary calculations. A sample from a single student can be seen in Table 2. Students were then asked to compare their commercial yeast kinetic parameters to published data.<sup>[43]</sup> The students experimentally determined that  $\mu_{max}$  and  $K_s$  were all in the same order of magnitude – and many within 10% – of reported values. Students also observed substrate inhibition on yeast and sourdough growth kinetics (see Figure 4b, where the sourdough starter has

decreased  $\text{CO}_2$  production at 1 tablespoon sugar added), as is expected for these systems. Double reciprocal plots had previously been used by students to determine Monod constants, an option that can be employed if students are less familiar with Excel, or if training students to use Solver in Excel for these experiments is not desired.

All instructions and the Excel templates distributed to students can be obtained by contacting the corresponding author at [chen.christopher@columbia.edu](mailto:chen.christopher@columbia.edu). A list of these materials can be found in the Appendix.

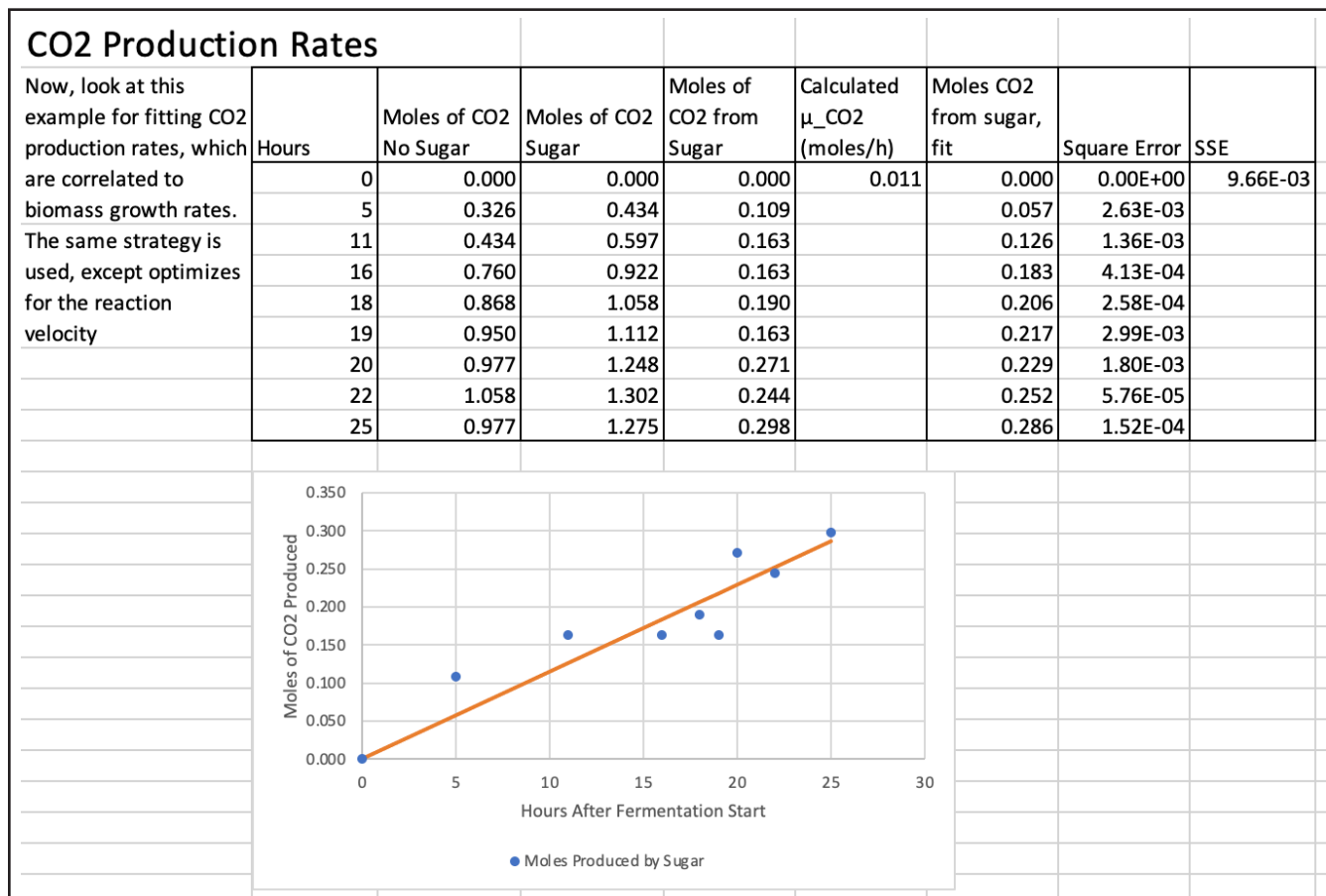


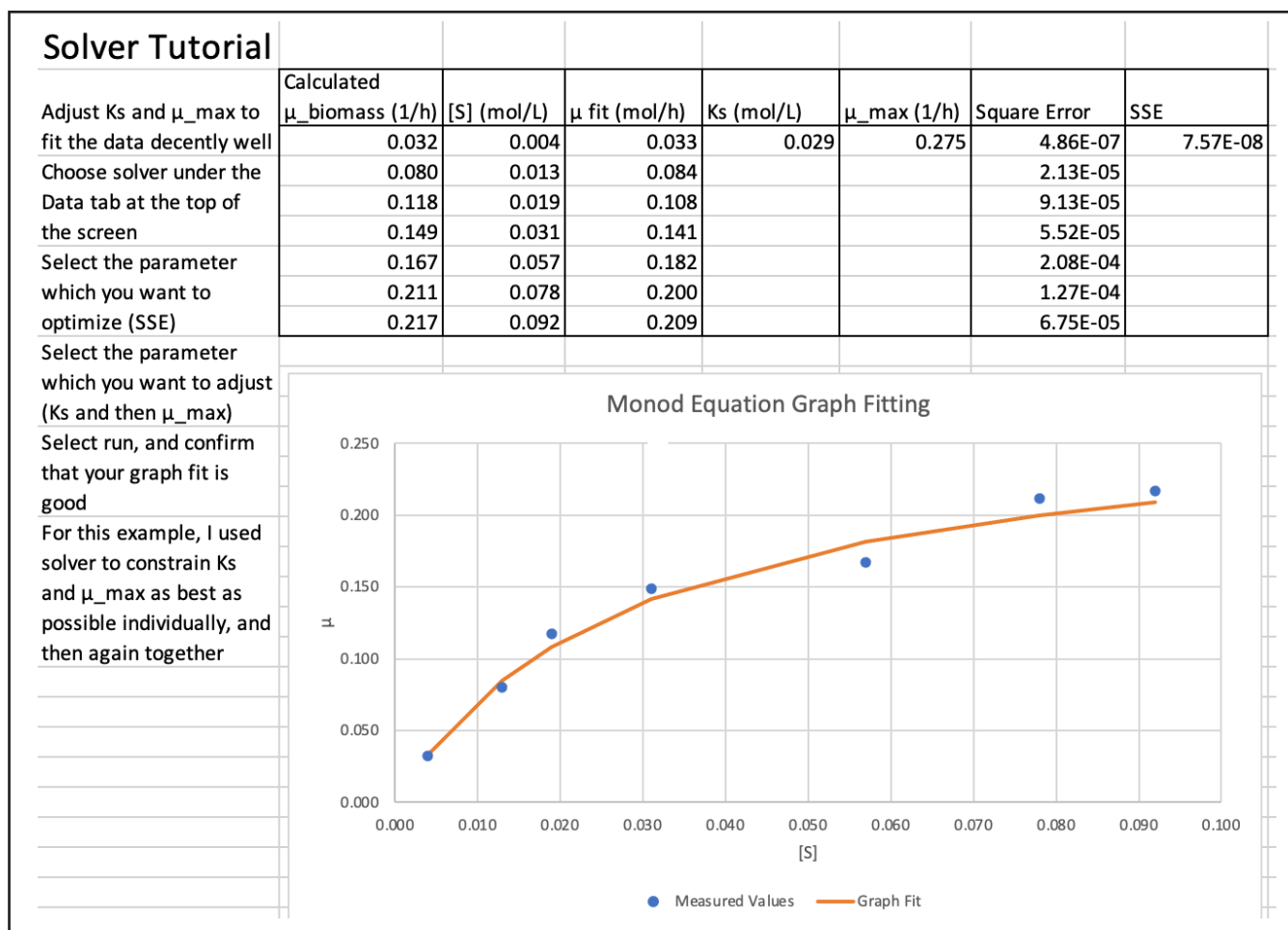
Figure 5. Example of Excel template that assists students in determining growth rates ( $\mu$ ) for their cultures.

## RESULTS AND DISCUSSION

A total of 19 students participated in the chemical engineering design project of The Art of Engineering course in the Fall 2020 semester, split into nine groups of two or three based on time zone. Students were encouraged to do the experiments during the weekly synchronous class meetings over Zoom<sup>®</sup> and receive immediate instructor feedback. Pairs and trios served as a means of support for conducting the experiments outside of synchronous class meetings. Each pair and trio jointly gave their final presentation – a PowerPoint<sup>®</sup> deck delivered live during a sixth synchronous Zoom meeting – and responded to comments and questions from instructors and the class. Two groups (totaling four students) participated fully asynchronously and submitted their final project by submitting a recorded video.

During the Fall 2021 and Spring 2022 semesters, the module was taught online synchronously and gradually incorporated more in-person learning. In Fall 2021 groups were randomly assigned and encouraged to collaborate to share data with their group members. Group members were presented with the opportunity to collaborate with each other

in person, outside of class time, which was not mandatory for module completion. In the following iteration of the module, students were encouraged to form their own groups to compare results and present in-person. The option to form groups for in-person presentations resulted in an increase of students who chose to work together compared to the prior semester. The Fall 2022 course was completely in-person. Students selected their own partners and were encouraged to share samples and results outside of their groups. For the final presentation the students in the last iteration elected to collaborate in much larger groups when compared to the first two iterations. Since the first offering in Fall 2020, we have had more than 60 students successfully complete the sourdough starter experiments (with 19 students in Fall 2020, 14 students in Fall 2021, 11 students in Spring 2022, 9 students in Fall 2022, and 12 students in Spring 2023). Given the variability in the equipment the students used, all student teams were able to produce reasonable data from their remote experiments as demonstrated by their ability to experimentally determine Monod growth parameters for baker's yeast (with many groups within 10% of reported values, and all teams within the same order of magnitude).



**Figure 6.** Example solver tutorial/Excel template for Monod equation graph-fitting where  $\mu_{max}$  and  $K_s$  are analytically determined parameters. Substrate inhibition is observed within most student-collected data.

	Baker's Yeast (Literature <sup>[43]</sup> )	Baker's Yeast (Measured)	Sourdough Starter
$K_s$ (g/L)	0.452	0.30	0.07
$\mu_{max}$ (hr <sup>-1</sup> )	0.304	0.28	1.0

\*Baker's yeast  $K_s$  was determined from Excel template and converted to g/L to compare against literature values.

Comprehension of basic principles of material balances and growth kinetics were assessed via check-in quizzes on Canvas®, which all students passed (see sample questions in Appendix). In the first iteration of the module (Fall 2020), 12 of 19 students responded to a final survey of mostly Likert scale questions, where 92% of respondents reported having learned a considerable amount and ranked the lab as excellent overall. 58% of students indicated the hands-on

activities had an appropriate workload, which we view as exceptional given that all experiments were run outside of class meetings and that students were unlikely to have been asked to participate in a remote lab before. In the free response portion of the survey, half of the students mentioned that they appreciated the open-ended nature of the experiments, and a quarter indicated that they would recommend additional lecture content or support in future iterations of the lab. (Survey questions are available by contacting the corresponding author at [chen.christopher@columbia.edu](mailto:chen.christopher@columbia.edu).)

In the first all in-person run of these experiments in Fall 2022, six of nine students responded to the final survey, where all six respondents reported having learned a considerable amount and five of six ranked the lab as excellent overall (the remaining student ranked the lab as neutrally good). One challenge that arose from running these experiments as part of an in-person, residential course was that half of students reported having difficulties keeping their sourdough starters in their dorms due to complaints from people

with whom they lived. These complaints were mostly from smells in the first few days of these cultures. As these cultures simply grow from bacteria in the environment, however, odors were found to be less tolerable when grown in spaces that likely contained foul-smelling microorganisms. For example, the starter of one student team who grew their standard sourdough starter in a cabinet above a stove in their dorm kitchenette was found to be particularly smelly – so much so that the resident assistant on the floor asked the team to dispose of their cultures immediately. However, because these problems arose, students who ran the experiments during this semester were more likely to share starters, which added to the collaborative nature of the project. Student feedback was therefore predominantly focused on recommendations that would help better support students in finding space within the department where they could keep their samples as they grew, which helped reduce these difficulties reported by students in the Spring 2023 run of these experiments.

Another change we suggest implementing is growing sourdough cultures when indoor conditions are relatively stable, which may vary based on student or school location. Many students who took the course in Fall 2022 ran into issues with their cultures adapting poorly to fluctuations in heat and humidity in student housing (with many cultures dying when the heat was suddenly turned on). Having students refrigerate their sourdough culture between experiments after it reliably ferments would help to prevent the starters from adjusting poorly to new humidity and temperature, reduce the complaints received from dormmates, and allow the students to focus on the experiments rather than ensuring that their starter is continually growing.

### Addressing Diversity, Equity, and Inclusion

Following our approach to inclusive teaching – with the goals of making learning activities meaningful, relevant, and accessible to all – allowing our students to engage with us in authentic inquiry has enabled our students to bring more of themselves into the lab. For instance, we encouraged students to think of locally available fermented food that could act as sources of microorganisms for subsequent experiments. One student from South Korea used kimchi as their source food (likely culturing *Leuconostoc mesenteroides* and *Lactobacillus kimchi*).<sup>[44]</sup> Other students used yogurt with live and active cultures (*Lactobacillus acidophilus* and *Streptococcus thermophilus*)<sup>[45]</sup> and sediment from wine bottles (likely primarily *Saccharomyces cerevisiae* wine yeast, *Kloeckera* and *Candida* sp.).<sup>[46]</sup> Since experiments only measured carbon dioxide as a by-product of metabolic processes, we encouraged students with alternate cultures to analyze differences in product formation between their microbes and class sourdough data.

Additionally, students are encouraged to consider audiences and problems that may appeal to themselves as people as they prepare their pitch applications for a selected sourdough starter. This has led to students targeting all sorts of populations that could benefit from scaleup of their sourdough starters (e.g., starters that could be used to create baked goods that were more preferable to certain individuals, such as aligned with religious or cultural events, etc.).

Allowing students to participate in the majority of laboratory activities at home also improves the lab's accessibility. Student schedules are complicated, so allowing student teams to share and self-schedule lab work done in their residences facilitates students to engage at convenient times. The previous potential hardships of taking up space in a kitchen or bathroom when at home or outlaying additional funds to purchase materials for these experiments have also been removed with the return to in-person instruction as the department now distributes all materials to students that are necessary for completion and offers a location for the storage of starters, if needed. Students still are able to supply their own materials or equipment (e.g., UV lighting for curing nail polish used as a light source under which sourdough culture was grown, other sources of bacteria or yeast, or alternative liquids for growing sourdough such as milk, juice, and other beverages.) Students can also suggest materials to be considered for purchase for their experiments by the department. This has resulted in experiments where students have varied conditions such as concentrations of salt (by adding sweat), pH (by adding fruit juice), type of sweetener (adding sucralose instead of sucrose), and temperature (by varying storage conditions).

We recognize the potential challenges for students who have jobs or other obligations at home of having to participate in these labs predominantly outside of class time. These challenges are addressed by having students participate as teams and encouraging coordination that helps to alleviate daily duties related to these experiments by any one student.

## CONCLUSION

We presented the design of a six-week hands-on module for first-year engineering students that was developed during the COVID lockdowns and has continued as we transitioned back to in-person instruction. This experiment uses sourdough starter as a platform that facilitates authentic inquiry as students learn about chemical engineering approaches to experimental design and problem solving. By focusing on sourdough starter, the hands-on module was able to be run safely and remotely at home with students able to use materials and equipment they already had on hand (typically found in a residential kitchen), with additional expenditures

expected to be no more than \$5 to participate fully. All materials are now directly distributed by the department at no additional cost to students.

Over 60 students have successfully completed this experimental module since Fall 2020 both remotely and in-person. Following the protocols and using common tools found at home, students have been able to characterize the growth kinetics of their starters and compare them to commercial yeast kinetics that they also measure at home. Many students are able to get within 10% of reported Monod growth parameters for baker's yeast, and all groups have measured the same order of magnitude, demonstrating the robustness of the experimental protocols despite the low precision of home measuring devices.

Based on positive responses to the sourdough module – both remotely and in-person – we plan to continue with this line of experiments. In the future, we would like to create more robust assays for measuring cell growth that leverage common laboratory materials that could be safely distributed for home use or departmental laboratory space. For example, lactic acid bacteria growth can be estimated via pH, so distributing samples of pH paper could be a way of measuring growth kinetics of species other than carbon dioxide-producing yeasts. We also hope to further encourage our students to explore using the sourdough starter as an authentic inquiry platform within this first-year module, in subsequent chemical engineering core courses such as Material & Energy Balances or Reaction Kinetics, or in electives in biochemical engineering or bioreactor design. This would help to engage our students in more advanced experimental and engineering design while maintaining the experiment's meaningfulness, relevance, and accessibility.

## REFERENCES

1. Mistry N and Shahid N (2021) Design and delivery of virtual inquiry-based organic chemistry experiments. *Journal of Chemical Education*. 98(9):2952-2958. DOI: 10.1021/acs.jchemed.1c00571
2. Roller RM, Sumantakul S, Tran M, Van Wyk A, Zinna J, Donelson DA, Finnegan SG, Foley G, Frechette OR, and Gaetgens J (2021) Inquiry-based laboratories using paper microfluidic devices. *Journal of Chemical Education*. 98(6):1946-1953. DOI: 10.1021/acs.jchemed.1c00214.
3. Rossiter D, Petrusis R, and Biggs CA (2010) A blended approach to problem-based learning in the freshman year. *Chemical Engineering Education*. 44(1):23-29.
4. Chintalapati P (2022) Assessing the shift to an inquiry-based approach in 2nd year chemical engineering labs on observed student engagement and self-reported understanding. *Proceedings Canadian Engineering Education Association (CEEA)*. DOI: 10.24908/pceea.vi.15868.
5. Vigeant MA, Prince MJ, Nottis KE, and Miller RL (2011) Inquiry-based activities to address critical concepts in chemical engineering. *Proceedings ASEE Annual Conference*. DOI: 10.18260/1-2--18186.
6. Cokar M, Arredondo JH, and Wong MS (2021) An inquiry-based learning undergraduate laboratory course during the COVID-19 pandemic. *Chemical Engineering Education*. 55(2):85-85. DOI: 10.18260/2-1-370.660-126873.
7. Panebianco CJ, Iatridis JC, and Weiser JR (2022) Teaching principles of biomaterials to undergraduate students during the COVID-19 pandemic with at-home inquiry-based learning laboratory experiments. *Chemical Engineering Education*. 56(1):22-35. DOI: 10.18260/2-1-370.660-125552.
8. Korolija JN, Plavsic JV, Marinkovic D, and Mandic LM (2012) Beer as a teaching aid in the classroom and laboratory. *Journal of Chemical Education*. 89(5):605-609. DOI: 10.1021/ed200187c.
9. Hooker PD, Deutschman WA, and Avery BJ (2014) The biology and chemistry of brewing: an interdisciplinary course. *Journal of Chemical Education*. 91(3):336-339. DOI: 10.1021/ed400523m.
10. Pelter MW and McQuade J (2005) Brewing science in the chemistry laboratory: A "mashing" investigation of starch and carbohydrates. *Journal of Chemical Education*. 82(12):1811. DOI: 10.1021/ed082p1811.
11. Nielsen RP, Sørensen JL, Simonsen ME, Madsen HT, Muff J, Strandgaard M, and Søgaard EG (2016) Brewing as a comprehensive learning platform in chemical engineering. *Journal of Chemical Education*. 93(9):1549-1555. DOI: 10.1021/acs.jchemed.5b00994.
12. North M (1998) The baker's yeast reduction of keto-esters in organic solvents: a one week research project for undergraduate students. *Journal of Chemical Education*. 75(5):630. DOI: 10.1021/ed075p630.
13. Patterson J and Sigurdsson ST (2005) Use of enzymes in organic synthesis: reduction of ketones by baker's yeast revisited. *Journal of Chemical Education*. 82(7):1049. DOI: 10.1021/ed082p1049.
14. Koutsokali M and Valahas M (2020) Anaerobic and aerobic respiration in yeast: small-scale variations on a classic laboratory activity. *Journal of Chemical Education*. 97(4):1041-1047. DOI: 10.1021/acs.jchemed.9b00994.
15. Weinberg RB (2018) Measuring yeast fermentation kinetics with a homemade water displacement volumetric gasometer. *Journal of Chemical Education*. 95(5):828-832. DOI: 10.1021/acs.jchemed.7b00043.
16. Taber RL and Harwood BG (1983) Yeast metabolism of D-[U-14C]-glucose: A student study of the early stages of glycolysis. *Journal of Chemical Education*. 60(3):249. DOI: 10.1021/ed060p249.
17. (1967) Engineering courses emphasize the practical. *Chemical & Engineering News*. 45(42):52-54. DOI: 10.1021/cen-v045n042.p052.
18. VanDerWerff E. How to bake bread. *Vox* 2020.
19. Delap J (August 4, 2020) Why sourdough went viral. *The Economist*. <https://www.economist.com/1843/2020/08/04/why-sourdough-went-viral>. Accessed on May 22, 2021.
20. Thomsen KK (2008) Production of  $\alpha$ -amylase by yeast. *Critical Reviews in Biotechnology*. 5(3):205-215. DOI: 10.3109/07388558709086979.
21. Müller V (2001) Bacterial fermentation. DOI: 10.1038/npgeels.0001415.
22. Gunsalus IC (1948) Bacterial metabolism. *Annu Rev Biochem*. 17:627-56. DOI: 10.1146/annurev.bi.17.070148.003211.
23. De Vuyst L and Vancanneyt M (2007) Biodiversity and identification of sourdough lactic acid bacteria. *Food Microbiol*. 24(2):120-7. DOI: 10.1016/j.fm.2006.07.005.
24. Iosca G, Vero LD, Gullo M, Licciardello F, Quartieri A, and Pulvirenti A (2020) Exploring the microbial community of traditional sourdoughs to select yeasts and lactic acid bacteria. *Proceedings 1st International Electronic Conference on Microbiology*. 66(1):3. DOI: 10.3390/proceedings2020066003.
25. Carbonetto B, Nidelet T, Guezenc S, Perez M, Segond D, and Sicard D (2020) Interactions between *Kazachstania humilis* yeast species and lactic acid bacteria in sourdough. *Microorganisms*. 8(2). DOI: 10.3390/microorganisms8020240.

26. García Vilanova M, Díez C, Quirino B, and Iñaki Álava J (2015) Microbiota distribution in sourdough: Influence of high sucrose resistant strains. *International Journal of Gastronomy and Food Science*. 2(2):98-102. DOI: 10.1016/j.ijgfs.2015.01.002.
27. Gobetti M and Corsetti A (1997) Lactobacillus sanfranciscoa key sourdough lactic acid bacterium: a review. *Food Microbiology*. 14(2):175-187. DOI: 10.1006/fmic.1996.0083.
28. Ehrmann MA and Vogel RF (2005) Molecular taxonomy and genetics of sourdough lactic acid bacteria. *Trends in Food Science & Technology*. 16(1-3):31-42. DOI: 10.1016/j.tifs.2004.06.004.
29. Randazzo CL, Heilig H, Restuccia C, Giudici P, and Caggia C (2005) Bacterial population in traditional sourdough evaluated by molecular methods. *J Appl Microbiol*. 99(2):251-8. DOI: 10.1111/j.1365-2672.2005.02624.x.
30. Gaglio R, Alfonso A, Polizzotto N, Corona O, Francesca N, Russo G, Moschetti G, and Settanni L (2018) Performances of different metabolic lactobacillus groups during the fermentation of pizza doughs processed from semolina. *Fermentation*. 4(3):61. DOI: 10.3390/fermentation4030061.
31. Holt BH, Buchan A, DeBruyn JM, Goodrich-Blair H, McPherson E, and Brown VA (2022) Breaking barriers with bread: using the sourdough starter microbiome to teach high-throughput sequencing techniques. *Journal of Microbiology & Biology Education*. 23(2):e00306-21. DOI:10.1128/jmbe.00306-21.
32. Akdoğan H and Özilgen M (1992) Kinetics of microbial growth, gas production, and dough volume increase during leavening. *Enzyme and Microbial Technology*. 14(2):141-143. DOI: 10.1016/0141-0229(92)90172-k.
33. Chavan RS and Chavan SR (2011) Sourdough technology - A traditional way for wholesome foods: A review. *Comprehensive Reviews in Food Science and Food Safety*. 10(3):169-182. DOI: 10.1111/j.1541-4337.2011.00148.x.
34. Gelinis P (2010) Mapping early patents on baker's yeast manufacture. *Compr Rev Food Sci Food Saf*. 9(5):483-497. DOI: 10.1111/j.1541-4337.2010.00122.x.
35. Katina K, Heiniö RL, Autio K, and Poutanen K (2006) Optimization of sourdough process for improved sensory profile and texture of wheat bread. *LWT - Food Science and Technology*. 39(10):1189-1202. DOI: 10.1016/j.lwt.2005.08.001.
36. Buck LB, Bretz SL, and Towns MH (2008) Characterizing the level of inquiry in the undergraduate laboratory. *Journal of College Science Teaching*. 38(1):52-58.
37. Rowland S, Pedwell R, Lawrie G, Lovie-Toon J, and Hung Y (2016) Do we need to design course-based undergraduate research experiences for authenticity? *CBE—Life Sciences Education*. 15(4):ar79. DOI: 10.1187/cbe.16-02-0102.
38. Wu XB, Sandoval C, Knight S, Jaime X, Macik M, and Schielack JF (2021) Web-based authentic inquiry experiences in large introductory classes consistently associated with significant learning gains for all students. *International Journal of STEM Education*. 8(1):31. DOI: 10.1186/s40594-021-00290-3.
39. White J and Munns DJ (1951) Influence of temperature on yeast growth and fermentation. *Journal of the Institute of Brewing*. 57(4):280-284. DOI: 10.1002/j.2050-0416.1951.tb01628.x.
40. McKenney E, Madden AA, Nichols L, and Dunn R. Wild Sourdough. <http://robdunnlab.com/projects/wildsourdough/#makestarter>. Accessed on September 30, 2020.
41. Aranda OP, Matallana (2019) Yeast life span and its impact on food fermentations. *Fermentation*. 5(2):37. DOI: 10.3390/fermentation5020037.
42. Monod J (1949) The growth of bacterial cultures. *Annual Review of Microbiology*. 3(1):371-394. DOI: 10.1146/annurev.mi.03.100149.002103.
43. Wasungu KM and Simard RE (1982) Growth characteristics of bakers' yeast in ethanol. *Biotechnology and Bioengineering*. 24(5):1125-1134. DOI: 10.1002/bit.260240509.
44. Jung JY, Lee SH, Kim JM, Park MS, Bae JW, Hahn Y, Madsen EL, and Jeon CO (2011) Metagenomic analysis of kimchi, a traditional Korean fermented food. *Appl Environ Microbiol*. 77(7):2264-74. DOI: 10.1128/AEM.02157-10.
45. Ng EW, Yeung M, and Tong PS (2011) Effects of yogurt starter cultures on the survival of Lactobacillus acidophilus. *Int J Food Microbiol*. 145(1):169-75. DOI: 10.1016/j.ijfoodmicro.2010.12.006.
46. Belda I, Zarraonandia I, Perisin M, Palacios A, and Acedo A (2017) From vineyard soil to wine fermentation: microbiome approximations to explain the "terroir" Cconcept. *Front Microbiol*. 8:821. DOI: 10.3389/fmicb.2017.00821. □

## APPENDIX

### List of Supplementary Materials Available by Contacting [chen.christopher@columbia.edu](mailto:chen.christopher@columbia.edu):

- Protocols and Excel templates distributed to students
- Surveys used to collect data

### Annotated Sample Material Balance Calculation Question:

You run a bread factory and you need 50 grams of yeast biomass. What is the total mass of sugar you need for stoichiometric production? Use the equation below and round your answer to two decimal places, given in grams.



Correct answer: 130.18 (g).

Correct responses: 11/15

Common errors on this question were either from a miscalculation of molecular mass (of yeast or sugar) or from incorrect stoichiometry used (i.e., forgetting to use stoichiometric coefficient). This question stems directly from discussions of these type of calculations for the sourdough starter reaction yield experiments done in the first two weeks.

### Annotated Sample Closed System Concept Question:

What's the difference between an open system (your microbe farm) and a closed system (your balloon bottle)?

- a) No mass can enter or exit a closed system
- b) Acid will be generated in an open system
- c) Yeast grow faster in an open system
- d) The temperature of the closed system will be higher

Correct answer: A

Correct responses: 14/15

This question reflects the discussion of why we run our sourdough starter carbon dioxide production experiments the way that we do, and connects to why we do batch (instead of continuous) material balance calculations for this exercise.

### Suggestions for Measuring Carbon Dioxide Generated in a Non-spherical Balloon:

- Students have conducted these experiments by partially inflating the balloons to make them more spherical. Though the change in circumference may be smaller (as the change in circumference at larger volumes is smaller with the same change in volume), accuracy is likely improved because the spherical assumption is better. This can lead to discussion with students as to when gauges are most accurate (accuracy at the extremes versus the middle of the gauge) and other experimental considerations of engineers.
- As suggested by a reviewer, students can create a calibration curve between circumference (or some other measure of balloon size) versus volume as using displaced water. Creating a calibration curve would open other types of experimental discussions, such as when and how to trust measurements given by any device, and how chemical engineers in practice validate the accuracy and/or precision of their instruments.