AC 2009-1438: A NOVEL OPEN-ENDED LIQUID-LIQUID EXTRACTION MODULE FOR THE CHEMICAL ENGINEERING LABORATORY

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Novel Open-Ended Liquid-Liquid Extraction Module for the Chemical Engineering Laboratory

Abstract

The evolution of Chemical Engineering imposes a unique challenge to the design of adequate modules in the laboratories. In this article we present a novel experimental module that we have designed and are currently implementing in the Chemical Engineering laboratory. The module includes topics of colloids, complex fluids and biotechnology, while also giving more emphasis to molecular interactions. The final objective of the long-term project is the extraction of lysozyme from egg white using Aqueous Bi-Phasic Systems. The project is divided between engineering teams in three phases: bench-scale experiments, the unit operation and the final extraction and scale-up calculations. Our focus is to implement a module that mimics the continuity of real engineering projects through the use of a sequence of sub-projects that are assigned to different groups in the class. The design of the long-term project forces students to deal with the various degrees of uncertainty that are associated with realistic open-ended problems. The approach is intended to provide a platform to teach and evaluate for an additional set of "soft" skills. These important skills include leadership, composure under uncertainty, critical thinking, creativity, group work, task division, time management, literature searches and forward thinking. We believe that the introduction of high degrees of uncertainty into the laboratory serves as a tool to prepare the students for a rapidly changing industrial world.

Introduction

The evolution of Chemical Engineering historically has been driven by changing industrial needs and by research developments in a broad spectrum of areas. Some of the relatively young areas of Chemical Engineering include semiconductors and microelectronics, nanotechnology, chemical product design, and biotechnology. [1-3] As a result, Chemical Engineering educators are continuously challenged to identify and teach a changing set of skills that students need to acquire to develop into successful engineers.[2,4] This imposes a unique challenge to the design and evolution of adequate modules for the chemical engineering laboratories. There is a particularly high degree of complexity associated with the economic, logistic and technical difficulties that are involved in implementing significant changes to large physical facilities and to the design of effective experiments that are suitable for instruction of these new and evolving concepts.

It is often believed that large investments of funds and effort are required to bring contemporary topics into older laboratories that teach the traditional unit operations such as distillation, heat exchange and reactor processes. In this article, we present our recent experiences in the design and implementation of a new experimental module that has been introduced in the second part of the Chemical Engineering laboratory sequence at the University of Washington using existing facilities and only a minor financial investment. Our primary aim is to modernize some of the laboratories by introducing concepts involving some of the latest developments in areas of biotechnology with emphasis on macromolecules. We also focus our effort in designing experimental modules that mimic the continuity of real engineering projects through the use of a sequence of sub-projects that are assigned to different groups in the class. The design of the long-term project forces students to deal with various degrees of uncertainty that are associated with realistic open-ended problems. In this lab, each of the sub-projects is assigned to a series of three-person engineering teams that are encouraged to collaborate and share their information. All of the groups' work, including experimental results, design calculations and recommendations, is provided to all teams who can decide to use it to design their own experiments and to perform scale-up calculations. An additional constraint that we had was that the new experimental module needed to be implemented within the normal operational budget of the laboratory.

The framework of the Chemical Engineering laboratories allows us to achieve high levels of uncertainty by introducing truly open-ended experimental modules while directly monitoring group dynamics. Furthermore, the interaction between different groups during the course will allow all students to evaluate the performance of other groups and to learn from each other's mistakes. The use of open-ended problems, classified also as project-based learning (PBL), is already highly valued by engineering departments that have embraced this form of instruction.[5-7] This teaching approach has been found to reinforce creative thinking,[8] to improve design quality[9] and to develop confidence and innovation skills.[10] Students are also more passionate when they are provided with challenging problems that do not have an obvious linear solution or a tightly constrained parameter space. [10-12] Offering project-based learning experiences enable the students to integrate technical design with real world constrains resulting in an increased and deeper understanding of their field. [6, 13-16] There is vast evidence in the arena of inductive learning and teaching methods that proves the positive influence of project-based learning in the development of skills such as: interconnecting and deeply understanding concepts, the application of reasoning strategies and team work.[17] Researchers in the area of Engineering Education have previously found through the use of meta-analyses the high value of project-based learning in classes that were traditionally taught using deductive teaching approaches.[18] We are proposing here that the use of open-ended projects in the laboratory can effectively illustrate to students the value of careful planning, effective communication, the critical evaluation of previous work and to keep composure when faced with high levels of uncertainty.

The equipment that is primarily used in this new module consists of a pilot scale reciprocating liquid-liquid extraction column (Karr Column).[19] The column had been previously used to perform extraction experiments involving solutes in organic and aqueous phases. The original module was a good representation of a real unit operation in a pilot scale. However, complications due to the use of volatile organic solvents and hazardous waste products resulted in the gradual simplification of the experiment over the years. At the time that we started teaching the laboratory, the Karr Column experiment was used to explore the concepts of mixing in a reciprocating column and for the evaluation of residence times using a dye and a single aqueous phase. The new module has resuscitated the old Karr Column back into a liquid-liquid extraction process without running into the safety and environmental problems of the past. In addition, the current focus includes contemporary engineering concepts such as the isolation of proteins using Aqueous Bi-Phasic Systems (ABS).[20-23]

Aqueous Bi-Phasic Systems, also known as Aqueous Two-Phase Systems, are formed when a water soluble polymer is combined with solutions containing certain inorganic salts or other water-soluble polymers at concentrations above critical values that define the binodal line. In the current experiment we focus specifically on polymer-salt systems. These systems form two distinct aqueous phases that are rich in either the polymer (light phase) or the salt (heavy phase). One of the great advantages of the system is that it can be implemented without the need to extensively modify the existing extraction column. Furthermore, the same equipment and module could be easily adapted in future years to other applications that involve current topics in Chemical Engineering. For example, ABS systems have been used or explored for the treatment of waste water,[23] and for the isolation of a variety of biological macromolecules such as proteins and lipids from complex fluids.[24] Our ABS system also offers a much safer and cleaner option due to the mild chemicals that are required in the separation. This is a great concern for engineering laboratories involving kilogram and gallon quantities of chemicals in their modules. Our new experimental module consists on students designing and implementing a continuous process for the extraction of lysozyme from egg whites. Lysozyme, a protein present in egg white and in secretions such as saliva and tears, serves as an antibacterial agent by interacting with the sugars in the bacterial wall.[25] In the new module, the isolation of the protein is used to introduce the topics of biotechnology and its applications to drug formulations.

From an educational perspective, the general idea of this module is to introduce important concepts of biotechnology and complex fluids into the large scale framework of a traditional unit operations laboratory. The quarter-long project is designed as follows: The first teams are asked to explore the appropriate conditions for the isolation of lysozyme using different polymer and salt concentrations and variations of pH. They are only provided with a memorandum broadly describing the task without any specific instructions or suggestions. The students are also provided with a couple of articles from the literature in order to jump start their search for additional information. This bench scale experiment forms the basis for the tasks assigned to the following teams as shown in figure 1. The next teams in the sequence are in charge of using the suggested “optimal” compositions from the first teams to scale the process and evaluate the possible configurations of the Karr Column. The second teams are also in charge of performing preliminary feasibility runs and identifying any operational or safety issues involved with the scale-up. The last teams in the quarter have the task to operate the column using all of the information of all previous groups. The groups must discriminate between useful data and flawed experiments to finally evaluate the separation of the proteins using real egg whites. At the end of the quarter twelve teams will be involved in the egg white extraction experiment. Each team has to present a planning report, an oral presentation and a final report. The oral presentations are open to the class so that the students are able to probe and question the data of previous groups and also monitor the progress of the long-term project.

Unexpected issues frequently arise in open-ended problems and we want to evaluate how the students deal with them and with the uncertainty that is involved. Therefore, students are primarily evaluated by their performance under the circumstances and not necessarily by the experimental outcome. For example, we find that some groups are much more proactive than others when they encounter unexpected problems. The module also allows us to more closely evaluate the organizational skills of the students since they are not provided with the explicit instructions that they would usually get in other experiments. Our goal is to provide an exciting, open-ended project that is developed from the initial bench scale evaluation, pilot plant operations and finally through the performance of scale-up calculations for industrial implementation. From an educational perspective, the project is ideally suited to allow us to evaluate the behavior of individual students under high levels of uncertainty to which they have not been exposed in the past. The introduction of uncertainty into the Chemical Engineering laboratory serves as a tool to prepare the students for a rapidly changing industrial world full of unexpected scenarios.

Experimental Design

Materials:

Fifty pounds of polyethylene glycol or Carbowax, in N.F. F.C.C. grade powder form and with an average molecular weight of 3350 g/gmol, was purchased from Dow Chemical Company. The salts, K_2HPO_4, KH_2PO_4 and KOH, were obtained from J.T. Baker. Lysozyme and Albumin lyophilized powders from chicken egg were obtained from Sigma-Aldrich. Dried chicken egg whites were also obtained from Sigma-Aldrich. Deionized water was used throughout the experiment.

The Karr column system includes two Omegaflex peristaltic pumps from Omega Engineering Inc. The column has been modified to include multiple barbed ports that could be used for feeding and extraction of material. Students are also provided with flexible tubing, barbed fittings and valves so that they are able to configure the column in a variety of ways. In order to assess protein concentration in bench scale experiments, students also have access to an Evolution 300 UV-Vis from Thermo Scientific. To measure sample composition in solutions containing multiple proteins, the teams use size exclusion chromatography (SEC). The column, Bio-Basic Sec 300, from Thermo Scientific is connected into a Hitachi L-6200 Intelligent Pump and a L-4200 UV-Vis detector. The analytical tools available to measure the concentration of proteins and the composition of the solutions are available thanks to collaboration with departmental faculty. These tools are available to the engineering teams if they opt to use them in their experiment and they are not currently a fundamental part of the Chemical Engineering Laboratory. Other simple analytical tools, such as spectrophotometric activity assays or gel electrophoresis, could also be used to evaluate the efficiency of the separation. The tools used in this specific module represent those that are available to students in our department.

Experimental Framework

In order to further engage the students in the topic, assignments are given in the form of memos from "Management" to the engineering teams of a mock consulting company, Seattle Labs. Some reference materials including journal papers and an operational manual for the Karr Column are also provided to all the students. All additional references that are found by the students and/or the instructors during the course of the experiment are placed on a central website so that all the groups can access the information. The students are all required to design their own experiments in order to accomplish the objectives presented in the memo. The memo describes that our fictitious company has been approached by a client from the pharmaceutical industry who is interested in a new method to extract a potent mutant form of lysozyme using liquid-liquid extraction. After extraction, the protein will be used by our client in a drug formulation for a topical antibiotic. The experimental plan developed by the students is described in a planning report that is evaluated by the instructors to determine the progress of the team and to assess the likelihood of successful results. We find that the student’s response to assignments that are well framed within a realistic narrative is qualitatively different from those of students that are just provided with instructions that are not tied to a real world application.

First Phase: Bench-Scale Extractions

Engineering groups from four laboratory sections have been assigned with the task of performing initial bench-scale experiments to identify the ABS system that is most suitable to isolate lysozyme from the other major protein components of chicken egg whites (e.g. ovalbumin). They are told that the next groups will use their information to advance the project forward. Therefore, they must make observations about potential problems (e.g. compositions resulting in very high viscosities) that may be encountered by future groups who will attempt the separation in the column. Management (the instructors) has proposed the use ABS systems based on Carbowax, a commercial polyethylene glycol product PEG, and the inorganic salt K_2HPO_4, as shown in figure 2. The specific task for the first groups is to quantify and evaluate the effect of the ABS composition on the isolation of lysozyme. The final report must also include explicit recommendations on the suggested feed compositions to perform continuous separations in the pilot scale liquid-liquid extraction column (Karr Column). These compositions are then adopted by other engineering teams that will evaluate conditions for feasible operation in the pilot scale Karr Column. The final reports are thoroughly evaluated by the instructors and the uncorrected reports are forwarded to other engineering teams involved in the project. The following teams are now faced with the challenge of evaluating and distinguishing between the potentially useful or misleading results of the previous groups.

Second Phase: Karr Column Operation

In this part of the project, the engineering teams are asked to evaluate several possible modes of operation of the Karr Column. In addition to all of the reference materials, the teams in the second sub-project have access to all of the documentation produced by the previous groups involved in bench-scale experiments (a total of 4 reports). The students have to evaluate to what extent they will use the information provided by their peers. They must also decide on which datasets are complete enough to justify their choices. Previous groups in the project serve as consultants and students are encouraged to collaborate. The objectives for the second group are very loosely defined. Their general goal is to advance the project forward by performing preliminary scale-up tests using the recommendations and feed compositions that have been provided by the previous groups. Among their tasks, the teams have to determine the location of all of the feeds and extraction streams, choose between fractional and counter current column operation and determine the agitation limits before flooding occurs in the column. The students must also learn to operate the column and to control it so that steady state is reached. This is complicated due to the fact that the extraction of materials from the exit ports occurs through gravity and hydrostatic pressure. Figure 3 shows three different configurations for feed and extraction locations. These configurations of the Karr Column were proposed by students in a group that evaluated their feasibility in the laboratory. As a part of their assignment, students have to provide calculations and data to support their recommendations. In addition, they are required to operate the Karr Column with constraints on the total amount of material that they are allowed to use to complete their tests (e.g. maximum use of 10 lb of PEG). Thus, they need to consider methods to recycle their samples or to reuse their materials. This gives them a perspective on the value of having a good experimental design to minimize the cost of process development tests. Most student groups performing this initial scale-up decide to operate the column in full recycle mode without adding any added egg whites. This allows them to run the column continuously so that they can evaluate the performance of their chosen ABS system over a wide range of operating conditions (e.g. flow rates and agitation speeds).

Third Phase: Extraction of Lysozyme from Egg White

This constitutes the last part of the experiment to be performed by the third and last group of student engineers. Again the groups are granted access to all of the collected information and recommendations from previous teams (a total of 8 reports). The objectives of this sub-project are to assess the information provided by other teams and use it to perform a large-scale extraction of lysozyme from chicken egg whites. Due to the difficulty of this task, we encourage the engineering teams to collaborate with previous teams that act as consultants. Since all presentations are open, the progress of the project is shared with the whole class each step of the way. By the end of the quarter the final teams that will perform the extraction also share their assessment of the collected information and the performance of the lysozyme extractions.

Preliminary Results and Discussion

Discussion of Students' Response

We are currently testing the implementation of the first open-ended experimental module in the laboratory. The final objective of this long-term project is the extraction of lysozyme from egg whites using an Aqueous Bi-Phasic Systems. The project is currently divided between engineering teams in three phases: bench-scale experiments, initial pilot-scale testing and the implementation of the final continuous extraction. Students are in close contact with instructors during the laboratory sections. However, we just act as consultants only providing basic help and materials to the groups and supervision for the safe operation of the column.

The current seniors have already finished the first phase of the project (bench-scale experiments) and have found the separation to be feasible in bench top experiments. The teams involved in the second phase have also evaluated and used this information to settle on the ABS compositions that they believe will show the highest promise to isolate the lysozyme from the other proteins in egg whites. The second groups have also developed and started executing experimental plans to evaluate the operation of the Karr Column with their chosen ABS composition. One of the most interesting observations is that students quickly learn to appreciate the value of good information and the perils of trusting misleading information. For example, most of the groups involved in the second part of the project chose to use the same data sets from all of the first set of groups. When asked about this, the students explained that the chosen reports contained the most complete sets of information. This realization helped them to design their own experiments to attempt to provide similarly useful information to future groups. To do this, they had to explicitly decide not to attempt to do everything at once so that they could focus their effort on the next logical step to advance the project (e.g. to evaluate all possible column configurations before attempting to separate proteins). The students also quickly recognized the importance of communicating effectively with other groups even when it was completely optional. For example, groups of students involved in the second part of the project frequently asked questions to students in the first part during the class oral presentations and also during the laboratory period. The students that were previously involved in the project were also interested in following the progress of the project.

The second set of students also realized that the compositions that were identified by the first groups to have the best selectivity did not always perform effectively in the continuous liquid-liquid extraction column. Therefore, they recommended that the third groups should think hard before selecting an ABS composition to use. In addition, several qualitative observations were made that further justify the need for the inclusion of truly open-ended problems in the laboratory. For instance, we noticed that some students with excellent academic standing had a really difficult time planning for the open-ended experiments. We believe that this stems directly from the unusually high levels of uncertainty and loosely defined goals. We also observed that other students were extremely motivated to tackle the problem and usually planned very effectively. We believe that there may be a significant correlation between the student's participation in undergraduate research projects and their performance in open-ended experiments. This hypothesis remains to be determined quantitatively.

A questionnaire was also distributed among the students to address their response to the new experimental module. The complete survey, distributed after the completion of the first phase, is shown in Table 1. Students answered each question by choosing a number between 4 and 0, where 4 is strongly agree, 3 is agree, 2 is neutral, 1 is somehow disagree and 0 is completely disagree. The percent of students that agreed or strongly agreed to any given statement is defined as a positive response. Among the questions, students were asked if team work skills are important to develop and if they are relevant in industrial scenarios. The vast majority of students responded positively, demonstrating their awareness of the value team work skills once they start their careers. Students were also questioned about the importance of developing skills to critically evaluate other's work. Again we found a highly positive response among all students in the class (91%) and students involved in the first phase of the project (92%). This finding is particularly encouraging to the instructors since the ability to perform a critical evaluation of information is not specifically evaluated in most courses. Therefore, this type of experimental platform can serve as an effective tool to teach information assessment. The ability to discriminate useful from useless information is extremely valuable in contemporary times when there are significantly larger levels of information available to them.[26]

Table 1: Survey administered at the end of the first phase to students in the chemical engineering laboratory.

	All class*	**Just students involved***

	Positive Response (%)**	Average Score***	Positive Response (%)	Average Score
Do you believe there is a need to include additional contemporary topics in the Chemical Engineering laboratory?	**74**	3.04	**67**	3
Would you say that the protein extraction experiment involves contemporary topics?	**77**	2.95	**92**	3
Would you say that knowledge of Polymers and Colloidal Science topics is a necessity to new chemical engineering graduates?	71	2.89	67	2.75
Would you say that knowledge of topics in Biotechnology is a necessity to new chemical engineering graduates?	**56**	2.62	**50**	2.5
Would you say that knowledge in Polymer Science will give you a better chance to find a job as a Chemical Engineer?	78	2.87	67	2.75
Would you say that knowledge in Biotechnology will give you a better chance to find a job as a Chemical Engineer?	67	2.8	58	2.58
Would you say that a quarter -long multi-team project will prepare you better for industrial positions?	67	2.93	67	2.92
Do you think that team collaboration skills are important for student development?	**94**	3.51	**100**	3.67
Do you believe that team work skills are important when working in industry?	**98**	3.64	**100**	3.75
Was the protein separation laboratory more challenging than other experiments?	46	2.54	67	2.83
Do you think that the protein separation experiment is a more representative experiment for the work that current Chemical Engineering graduates are performing in industry?	19	2.15	17	2.17
Would you agree that being able to critically evaluate others work is an important skill for your development?	**91**	3.24	**92**	3.17
Did this experiment require you to do that?	69	2.78	64	2.64
Would you say that an open-ended experiment is more interesting to perform?	**53**	2.47	**67**	2.42
Are you more engaged than usual when working in a project with an uncertain outcome?	61	2.5	50	2.58
Are you confident of a successful outcome for this project? (Will the proteins be separated by the end of the quarter?)	**34**	2.29	**50**	2.17
Would you say that open-ended experiments are	**45**	2.52	**50**	2.42

a more useful approach to teach engineering concepts?				
Would you recommend the inclusion of additional experiments of this type?	**48**	2.45	**67**	2.67

*“All class” columns correspond to the results of the whole class while the “Just students involved” columns correspond to the students that performed the first phase of the experiment. The class sample number was 47 students. The students involved sample number was 12 students.

**The positive response is the percent of students that answer with strongly agree or agree.

*** In the survey students were asked to answer the questions using the following point system: 4 = Strongly Agree, 3 = Agree, 2 = Neutral, 1 = Somehow Disagree, 0 = Completely Disagree.

The chemical engineering teams were asked about the need to include more contemporary topics in the laboratory and 76% of the class agreed that there is a need to modernize the laboratory. In addition about two thirds of the students involved in the project agreed or strongly agreed with the statement that the new experimental module covers contemporary topics. This finding encourages us to develop modules that would incorporate new applications. The majority of the students in the class (71%) were in agreement with the need to include polymers and colloidal science in the chemical engineering curriculum. This demonstrates that most students are aware of the new fields involved in the chemical engineering practice. It also shows that most students are interested in the addition of modules that incorporate topics in polymers.

In the questionnaire we also addressed the students' response to the new teaching approach and the use of an open-ended project. Two thirds of the students that performed the experiments in the first phase found the experimental approach more interesting than other more structured experiments. However, only half of the students expressed that the open-ended approach was more engaging than other experiments. Some students did not find themselves more committed or involved in this experiment than in other traditional ones. However, a higher number of students enjoyed working on the new experimental module more than in other experiments. Only about half of the students involved in the experiment perceived the teaching approach as more useful. On the other hand, two thirds of the students involved in the experiment recommended the inclusion of more experiments of this type. We believe the later is proof that the students enjoyed working in this experiment due to the unique approach.

This new experimental module served the purpose to include uncertainty as a tool in the chemical engineering laboratory. Well structured experiments with a traditional approach are also useful in teaching more thoroughly the theoretical concepts that may involve more rigorous mathematical analysis. Therefore, our aim is not to switch to an open-ended approach for all of the experiments in the laboratory. The open-ended approach is intended to provide a platform to teach and evaluate for an additional set of "soft" skills. These important skills include leadership, composure under uncertainty, critical thinking, creativity, group work, task division, time management, literature searches and forward thinking. Some of these skills are not usually included in more traditional approaches to teaching the Chemical Engineering laboratory.

Discussion and Future Directions

The original idea behind this module was to introduce contemporary topics into a classical unit operations laboratory. Our principal focus was to provide experimental exercises in areas that would include topics of colloids, complex fluids and biotechnology, while also giving more emphasis to molecular interactions. The modified Karr Column experiment has provided a base to easily design a variety of modules with different scopes by just changing the materials that are used. For example, extensions of the same experimental module can be designed with the use of co-polymers or polymer-polymer ABS systems.[27,28] Another possibility involves exploring the separation of α-lactalbumin from β-lactalbumin,[29] the isolation of proteins or DNA from cell cultures[30,31] or the isolation of lipids from complex fluid mixtures.[32] In future years, we plan to change the scope of the experiment by using an aqueous two-phase system for the treatment of nuclear wastes.[33] The use ABS systems for the extraction of radioactive materials in the remediation of nuclear wastes of the Hanford site (Hanford, WA) has been previously suggested and this application will be of special regional interest to students at the University of Washington.[34] The extraction process can fundamentally be designed the same way as for the isolation of lysozyme from egg white. On the other hand, the difference in the solutes to be isolated would incorporate important topics in environmental chemistry.

We believe that there is a need to include more complexity in the chemical engineering laboratory so that students can effectively make the link between large scale unit operations and relevant molecular phenomena. We also think that novel concepts sometimes can be brought into the laboratory with just minor modifications to existing equipment through the use of some creativity and effort from faculty. The student response to more realistic sets of problems and to higher standards is usually very positive. We believe that students are much more engaged in the laboratory experiments when they understand that their work is relevant and realistic. For this reason, it is important to analyze, design and renew the concepts covered in the laboratory to develop modules that incorporate these contemporary topics.

Even though our original focus was based on broadening the topical areas that are covered by the experiments, we quickly realized that the new module allowed us to more effectively teach important 'soft' skills that are essential to the Chemical Engineering practice. We have designed a continuous experimental platform based on a quarter-long project. The project is divided into parts that are developed by teams that collaborate and pass their findings to following workers. The goal is to be able to mimic more closely the development of a real process in an industrial scenario. A big part of the sub-projects is the assessment of the information that is provided by other teams. Students need to decide whether or not this information will be useful and to what extent they will use it.

Finally, the most dramatic change from the student perspective is the addition of substantially higher levels of uncertainty. In other experimental modules, students are given a very clear set of objectives and extensive information to accomplish their task in a short period of time. In this module, students are presented with multiple options for material compositions, limited availability of resources and a wide range of possible column configurations without any clear short-term goals. Instead, the students are just asked to "advance the project forward" to the best of their judgment and to the best of their capacity so that the whole class is able to accomplish the long term goal of evaluating and scaling-up the separation. They are also encouraged to dismiss any of our suggestions if they find more promising leads. The outcome of the project as a whole is truly uncertain due to the complexity involved in decision making or assessing the information provided by the other engineering teams. Therefore, we can determine that the problem proposed is truly open-ended.

Conclusions

We have designed and implemented a new experimental module based on an open-ended approach. Our goal is to incorporate uncertainty and use it as a teaching tool. The exposure to high levels of uncertainty pushes students to be highly creative and to use their critical thinking. In the experiment, the student's final goal is to extract Lysozyme from egg white through the use Aqueous Bi-Phasic Systems and a liquid-liquid extraction column. The objectives are provided in the form of memorandums from "Management" to engineering teams working for a mock company. The project is divided between engineering teams in three phases: bench-scale experiments, the initial evaluation of the process and the final extraction and scale-up calculations. The students are required to critically evaluate reference materials including their uncorrected peer's work in order to complete their task. The student's response was generally positive as proven by the questionnaire administered after the completion of the first phase. We have successfully implemented an experiment which incorporates high levels of uncertainty, contemporary applications and core chemical engineering concepts using pre-existing equipment and a limited budget.

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Figures

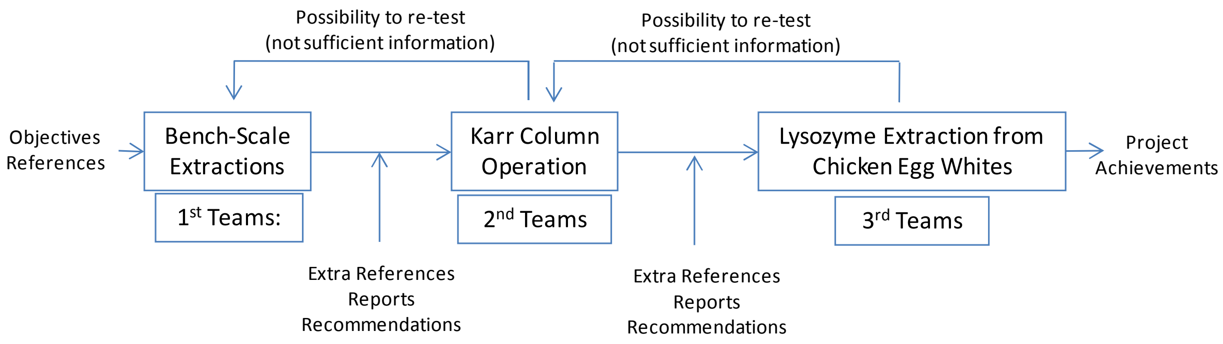

Figure 1: Representation of the new Karr column extraction experiment

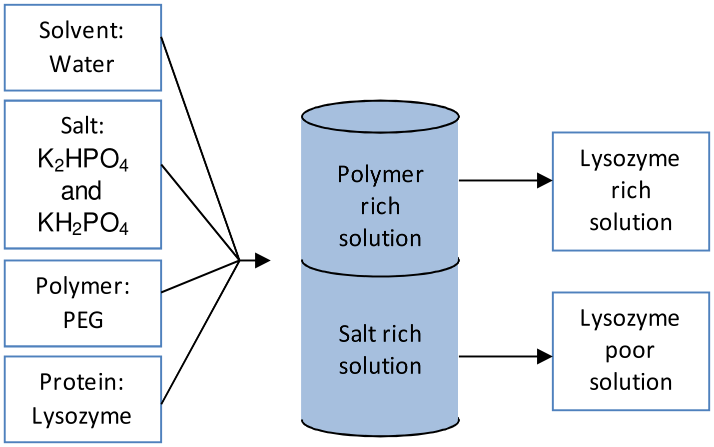

Figure 2: Schematic representation of bench-scale extraction

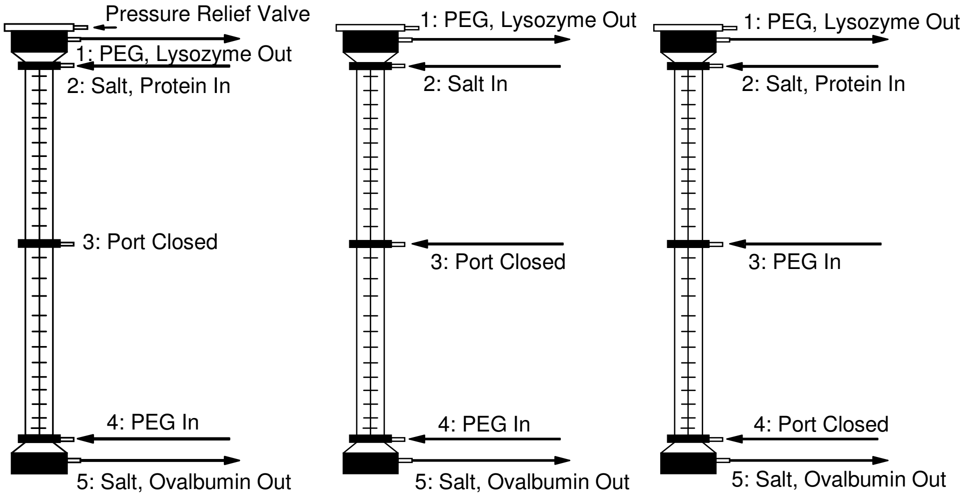

Figure 3: Diagram of the Karr Column, featuring multiple feed and extraction configurations. This figure was created by Sarah H. Widder in collaboration with Margaret S. Donegan-Ryan and Kyle M. Flotlin (students of the chemical engineering laboratory).