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At-Home Drug Delivery Experiment: Teaching Mass Transfer Using Food Dyes, DIY Spectrometer

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At-Home Drug Delivery Experiment: Teaching Mass Transfer using Food Coloring and a DIY Spectrophotometer

Abstract

The COVID-19 pandemic required many laboratory classes to be conducted online or in a hybrid fashion which motivated many educators to explore ways to provide hands-on learning opportunities for students who took courses remotely. Here, a simple at-home experiment is presented in which students studied mass transfer through designing an at-home drug delivery experiment. They utilized safe household items such as food coloring, cardboards, cell phones, and no special equipment. The goal of the experiment was to control the release of the food coloring (drugs), and deliver the most dyes over the longest time period (up to 7 days) from a drug carrier of their choice. They compared the experimental data with a diffusion (mass transfer) model and evaluated the results. The students also applied a two-compartment model to simulate the pharmacokinetics of the drug delivery.

Students wrote individual laboratory reports in the format of a research article (e.g. Journal of Controlled Release) which required them to present appropriate technical background, design of the experiments, results, analysis, and the overall findings. Written and oral feedback were given, and students were required to revise the report if not satisfactory. At least four learning outcomes were measured which includes: (i) design of experiments, (ii) analyze and interpret the results, (iii) written communication, and (iv) use of modern tools (e.g. MATLAB). Based on the assessments, the experiment was successful in achieving the expected learning outcomes.

Introduction

The need for hands-on experimentation in engineering laboratories has been well established and required in order to teach students many critical skills [1,3]. The traditional chemical engineering laboratory experiments expose students to the application of the core concepts such as fluids, heat transfer, mass transfers, thermodynamics, reaction kinetics, separation, and process control [2]. Even though the hands-on learning in a laboratory is an integral part of the undergraduate experience for the chemical engineering students, the COVID-19 pandemic forced universities and laboratories to close, leaving educators and students searching for ways to stay productive. Feisel and Rosa [1] outlined thirteen typical learning objectives for engineering laboratory courses. In a recent survey article, the AIChE Education Division Survey Committee reported the universal key educational outcomes for a laboratory course which includes Design of Experiment, Analysis and Interpret the Data, Effective Teamwork, Creativity, and Communication [2]. Although experience in a physical laboratory is critically important to become familiar with appropriate instrumentation and development of psychomotor skills and sensory awareness, most of the key outcomes can be achieved without requiring a physical laboratory space. The alternative approaches that have been reported in the literature to achieve these outcomes can be broadly categorized as: sending kits to home, providing students with videos of the experiment for analysis, simulation experiments, and at-home experiments [4-7]. The at-home lab approach enables researchers and students to explore science opportunities in their own homes with limited resources and space restrictions to achieve the learning outcomes while implementing safety protocols like social distancing.

Motivated by all these aspects, an at-home drug delivery experiment was developed and offered when the physical laboratory space was closed. In the two-week experiment, students were

required to design and test a drug delivery system to deliver small molecules of drugs (i.e. food coloring) and quantify the amount of drug released over time. Students were required to determine what factors controlled the release of the drug from the drug carrier, what conditions led to the greatest fraction of drug release, and compared the data to a theoretical model. Students were encouraged to think that many factors might contribute to the rate of drug release, including (but not limited to), type of drug carrier, the size, shape (e.g. core vs. core-shell structure), drug loading chemistry etc. We set a goal to deliver the drug over the longest time (up to 7 days) from the smallest device.

Students were exposed to the exciting field of drug delivery through this at-home experiment, (which was also very relatable during the pandemic) and experimentally validate the basic theories learnt for mass transfer. They designed a drug delivery system, built a DIY spectrophotometer that enabled them to determine the concentration of food coloring released over time. Spreadsheets and MATLAB were used to perform calculations necessary to determine and plot the release profiles and compared their experimental results to theoretical models. Therefore, through the experiment multiple learning objectives were assessed such as: (i) to design an open-ended experiment, (ii) to learn and validate the theories of mass transfer, (iii) to construct a DIY characterization tool (spectrophotometer), and (iv) to connect the experiment with a real-world application (i.e. drug delivery). In the following sections, the experimental design, examples of students' works, and specific student outcomes that were measured are presented.

Materials and methods

First, a survey was sent to the students to confirm the availability of necessary materials in their kitchen and a smart phone. A contactless pick up was also offered for any student in need of any experimental materials. During each at-home lab, students would log into a Webex meeting with their lab section and a graduate TA. The students were then separated into smaller, 3- to 4-person lab groups, to discuss their procedures and results, and both the instructor and the TA were available to assist and answer questions. Iterative feedback was given to individual student on their experimental design, and the final assessment was conducted through the lab reports written by individual student where specific questions were given to guide their analysis and discussion. The following sections described how typical experiments were conducted.

Sample Preparation

As mentioned before, the experiment was designed to be performed at-home. We had to keep in mind that students must not require any special equipment or chemicals that are not typically available at home, nor possess any safety risks. At the same time, the experiment should provide an authentic mass transfer laboratory experience and be accessible from an economic point of view. Furthermore, we believe a low-cost experimental design has the potential to be applied in the most diverse educational environments.

Therefore, all materials used in the experiment were available at home or in a grocery store such as food coloring, potatoes (or any similar items available in the kitchen), transparent glass cups, cardboard, piece of a colored paper, candle/wax, and a smart phone. Most of the students used

small cubes of potatoes as the drug carrier (i.e. to load the food coloring into it). The potato starch reinforced by cellulose is a natural polymer which can be heat treated to manipulate its fiber network (similar to manipulate cross-linking of a polymer) [8,9], it is also a very common item available in every kitchen, and is convenient to cut into any shape (i.e. square, sphere) and sizes.

Inn a typical experiment, the potatoes were peeled and roughly cut into cubes of $1cm^3$. They were then microwaved for a few minutes (1-5 minutes) to decrease the relative crystallinity of potato starch [8]. A few drops of food coloring were added to a known volume of water to make concentrated dye solution. The microwaved potatoes were then soaked into the dye solution overnight. The cubes of potatoes were taken out and dried.

The dye-loaded dried potato samples were then used for the mass transfer experiment. For a typical dye-release experiment, a potato cube was dropped to one transparent cup filled with about 100-200 mL of water and concentration of the dye in water was measured over a period of a few days. Steady state was assumed to be reached when no change in spectrometer reading was observed. A schematic of the sample preparation and the experimental process is shown in **Figure 1**.

DIY Spectrophotometer

To determine the concentration of released dye in water, a method of quantification was needed. A small piece of cardboard/box were used to cut into a DIY spectrophotometer as shown in **Figure 2.** The sample was placed against a light source (i.e. light bulb or natural day light) and the cell phone was used on other side of the box which detected the attenuated light through the sample. By quantifying the attenuated light, the concentration of the sample was determined using the Beer-Lambert law [10].

"*What a color?*", a freely available software (available on the Android and iPhone platforms), was used to measure the RGB (red−green−blue) signals collected from the samples. A digital image is made up of pixels, and each color is a combination of RGB channels. Any point with an intensity for each of the RGB channels is proportional to the light absorbed/transmitted by the samples.

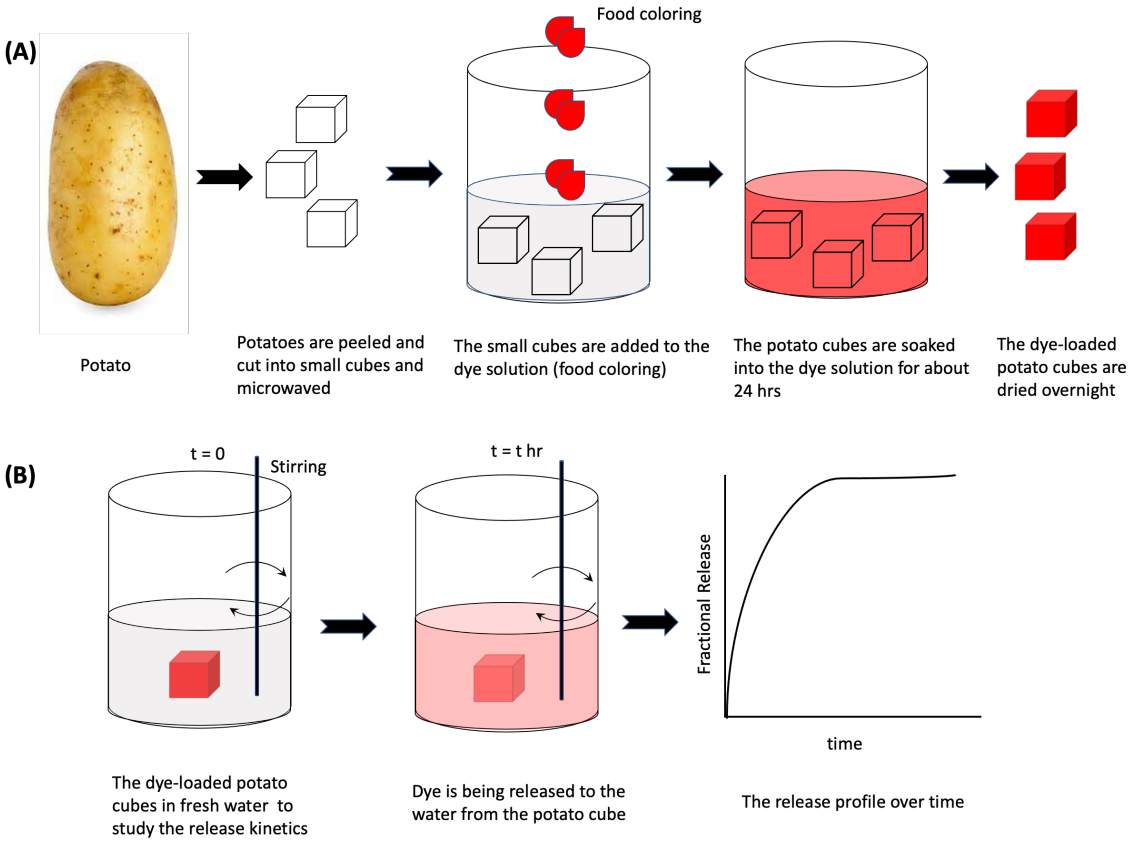

Figure 1. Schematics of: **(A)** sample preparation to study; **(B)** dye (drug) released from a potato and expected release trend over time.

A pixel took an integer value between 0 and 255 in each channel. By measuring the intensity of the attenuated light initially and at different time points, the absorbance of the samples was calculated [11]. Further, the students converted the absorbance to concentration of the sample (a sample work is presented in **Figure 3**).

Students were encouraged to use either the red, green or blue dye for the experiment. If red dye was chosen for the experiment, a green (or blue) colored paper was used as the backdrop. Then the intensity of the light detected in the Green channel was recorded and used for concentration calculation. Figure 2(B) shows the output of the "*What a color?*" App and how the signal intensities of different channels were displayed on phone.

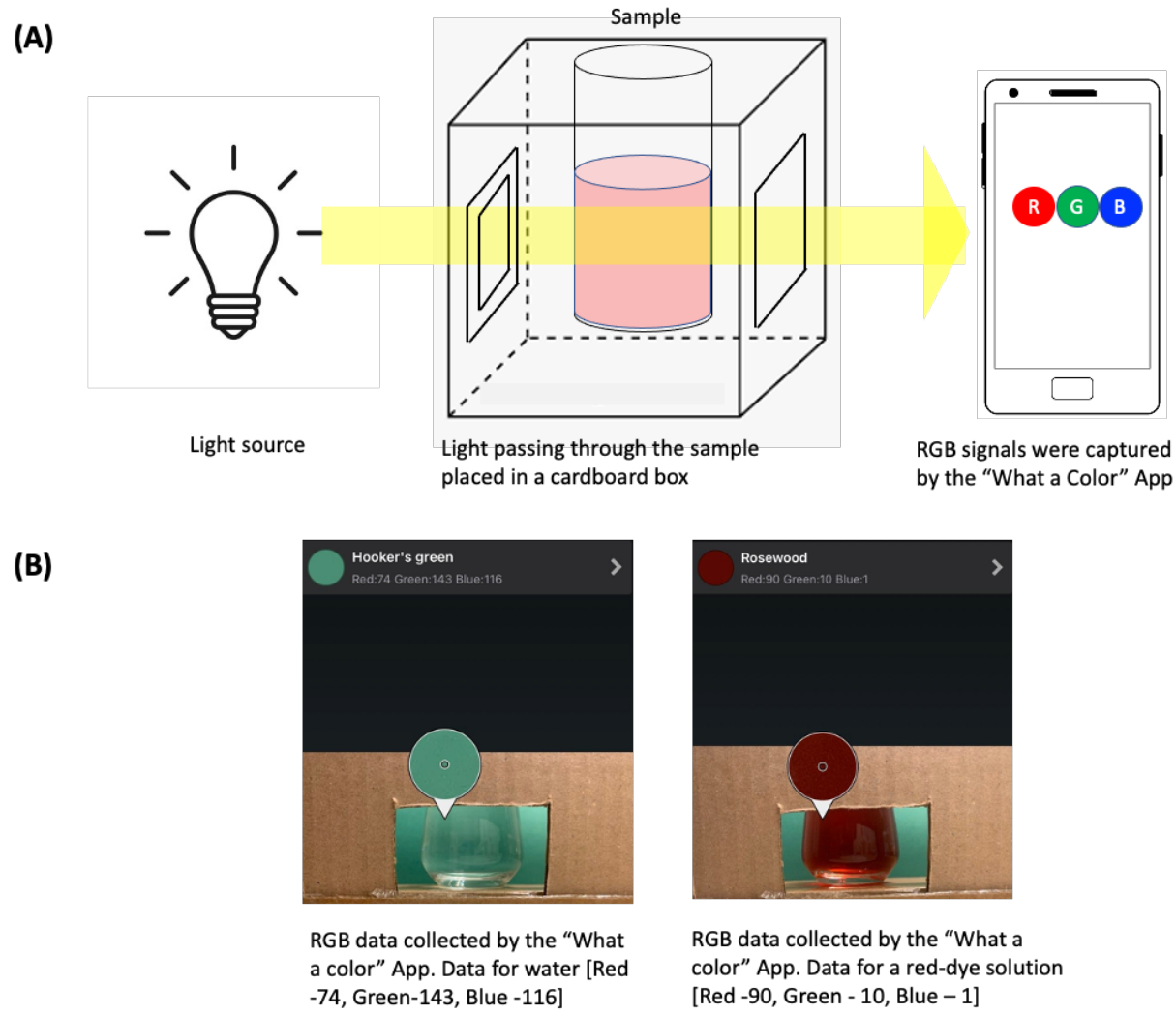

Figure 2. (A) Schematics of a DIY spectrophotometer; a cardboard was used to make boxes to hold the samples. The light passed through the sample went to a smart phone sensor which detected the RGB signal intensity; **(B)** An example of a simple set-up by a student. Signal intensity recorded for the individual samples are shown in their descriptions.

Calibration Curve

To determine the concentration of dye released over time, a calibration curve of absorbance versus concentration was constructed by all students. An example of student data table and calibration curve are shown in **Figure 3**. A linear relationship between concentration and absorbance was expected with some deviations. Students were required to report the correlation coefficient (R^2) in their analysis and comment on it. For the data presented in Figure 3, the correlation coefficient (0.987) was satisfactory. However, students reported correlation coefficient ranging from 0.80 - 0.98. While R^2 value close to 1 was expected, with the help of a DIY spectrometer and phone, a correlation coefficient (R^2) in that range was deemed reasonable for the scope of the experiment.

Concentration (a.u.)	Intensity recorded in the "Green" channel	Absorbance (a.u.)
0	143	0
0.125	88	0.21
0.25	54	0.42
0.5	35	0.61
0.75	19	0.87
1	10	1.15

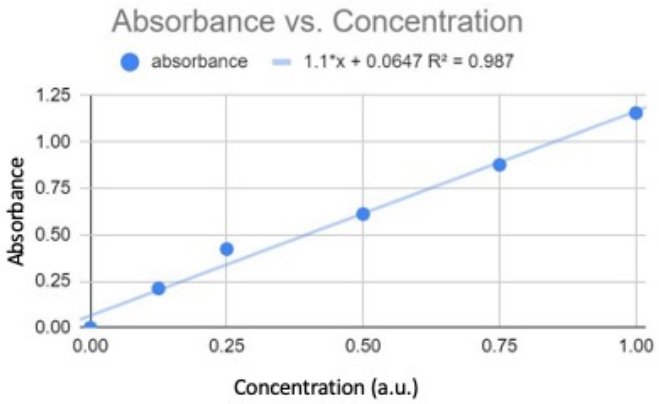

Figure 3. A sample student work of the calibration curve and associated data table that were generated from their DIY spectrophotometer.

Mathematical Modeling

Students compared the experimental observation with theoretical (diffusion) models. They mostly used the classic Fickian diffusion [12] or Ritger and Peppas model (Eq 2) to compare their observed results [13]. In either case, they were able to plot fractional drug release with respect to time as shown in the schematic of Figure 1B.

$$\frac{M_t}{M_\infty} = F = kt^n \qquad \text{(Eq 2)}$$

Where M, is the mass of drug released at time t, M_∞ is the mass of drug released after infinite time, F is the fraction released, k is a constant that depends on the diffusion coefficient and diffusion length, and n is an exponent which is indicative of the rate control mechanism. For Fickian diffusion in a slab, n = 0.5; in a sphere, n = 0.43.

Lastly, to connect the experiment with broader applications, the students developed a two-compartment pharmacokinetic model [14] (as shown in the Figure 4) and commented on the controlled release profile. Note students were asked to pick a model drug/tissue system and used the kinetic data reported in the research article. They developed a set of ordinary differential equations (ODE) and use of a computational tool such as MATLAB to plot the data. The overall goal of this part was to connect them with the broader impact of chemical engineering in drug delivery and related applications.

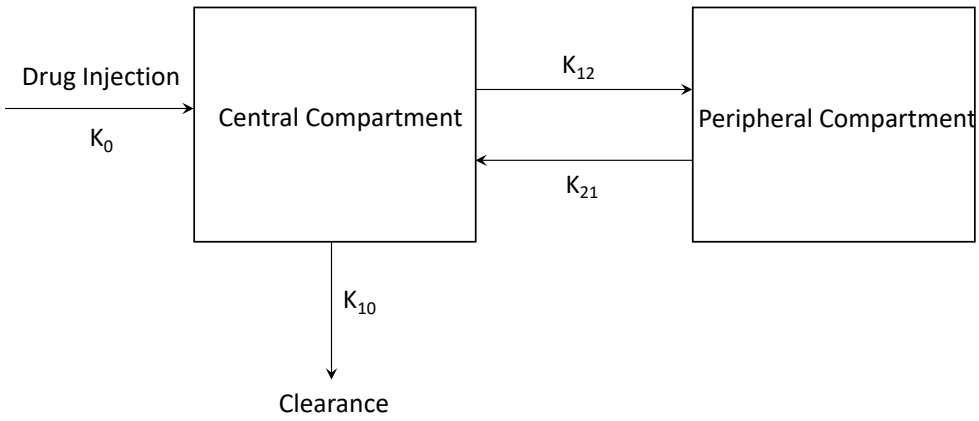

Figure 4. Schematic representation of a two-compartment model consisting of a central and peripheral compartment. Students determined concentrations in the compartments over time based on the kinetic data reported in the literature.

Results and discussion

Students summarized their work in the form of a report which required to be formatted as a research article. Students were also required to submit their measurement files, and their analysis files or codes (MATLAB and/or MS Excel). Through the lab reports, four critical skills were assessed to the extent possible, the skills are presented in terms of action words (of the Bloom's Taxonomy) as shown in **Table 1**. Examples of student works from the experiments are also shown in the following sections.

Table 1. Laboratory report (i.e. tasks) and accompanying skills targeted

Tasks	Skills Targeted
If students were able to:	
Summarize the problem into research question(s)	**Synthesis.** Relate knowledge from several areas i.e. compose, combine, create
Design the experiment in steps, at least identify variables to be manipulated and responding variables	**Evaluation.** Making choices based upon reasoned arguments
Predict the behavior or have hypothesis	**Synthesis.** Relate knowledge from several areas i.e. compose, combine, create
Collect and organize the data in table(s) that is logical and understandable	**Analysis.** Organization of parts. Identification of components (order, classify, arrange)
Plot the data that clearly depicts the summary of the experiment	**Analysis.** Organization of parts. Identification of components (order, classify, arrange)

Compare the theoretical models with the experiment	**Evaluation.** Verify the results. Use of modern tools, understanding the broader impact
Explains how the data and graph supports or refutes the prediction. Make recommendation for the future experiments	**Create.** Make choices based upon reasoned argument (assess, select, judge, summarize, compare and recommend)

Figure 7 shows examples of students' works i.e. samples prepared for the experiment and the DIY spectrophotometer set-up. While the absolute accuracy of the smart phone sensors and the arrangement of the experimental set-up varied, the experiments were designed to emphasize on the learning objectives that were independent of the sensor accuracy and appropriate for the undergraduate students. Here the main goals were to get them design the experiment, and the get data for further analysis.

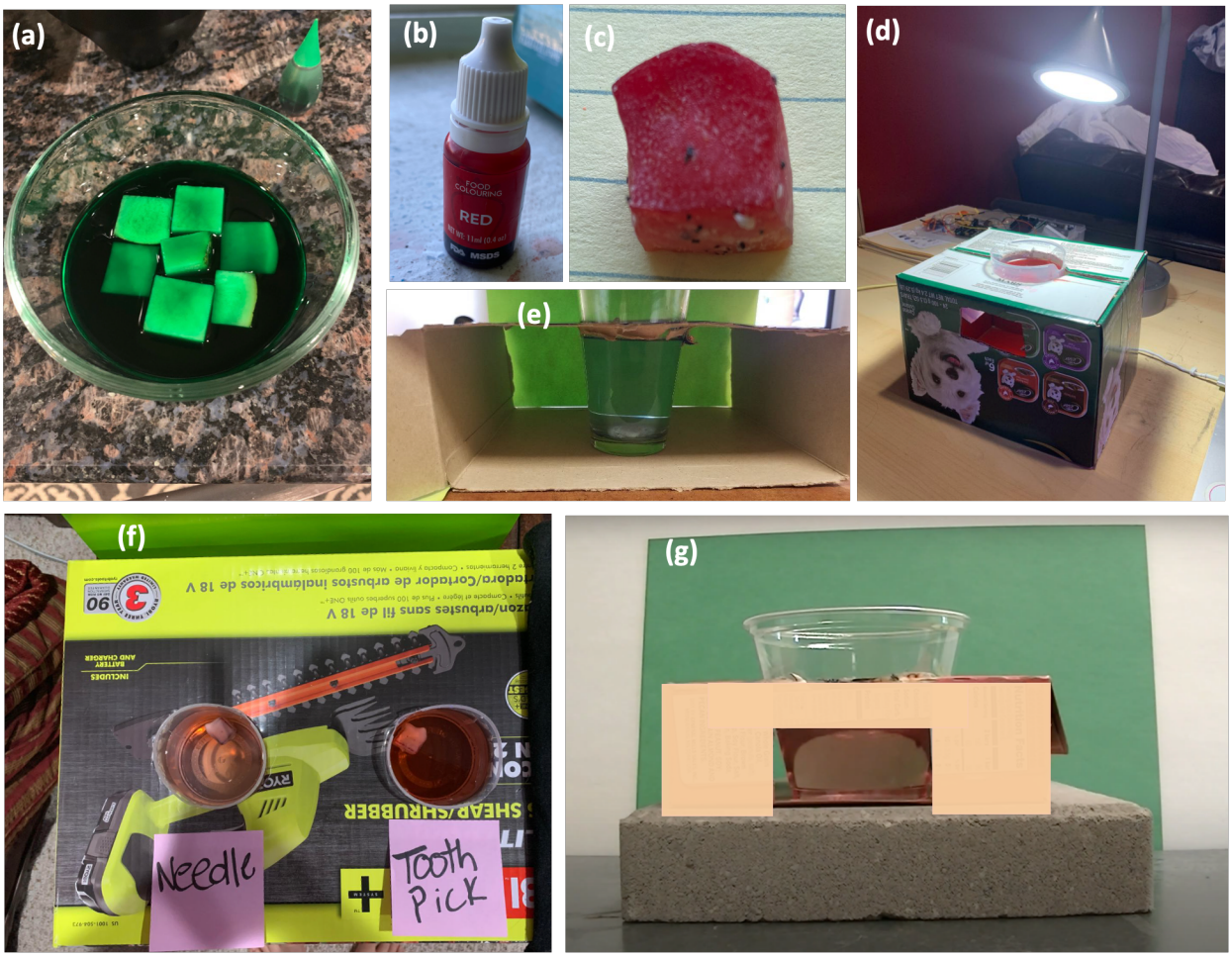

Figure 7. Example of students' works: (a) potatoes soaked in the green dyes, (b) a bottle of red food coloring (c) dried red potato cubes that was prepared for the release study. (d-g) A few examples of the spectrophotometer set up reported by the students.

Figure 8 shows four representative release profiles reported by the students. Note, students were tasked to maximum the release for up to 7 days. If they observed the fractional release curve reached a plateau within a day or in a few hours, they applied different techniques to slow down the release. Examples included: to coat the potato with wax or any other secondary layer (Figure 8b, 8c); for wax holes of different sizes was made to control the excess of water with the potato surface etc (Figure 8a, 8c). However, in all cases students observed the expected trends and reported reasonable release plots. Note, figures from students' reports have been directly used in Figure 8 without any modification, therefore some texts on the plots are small.

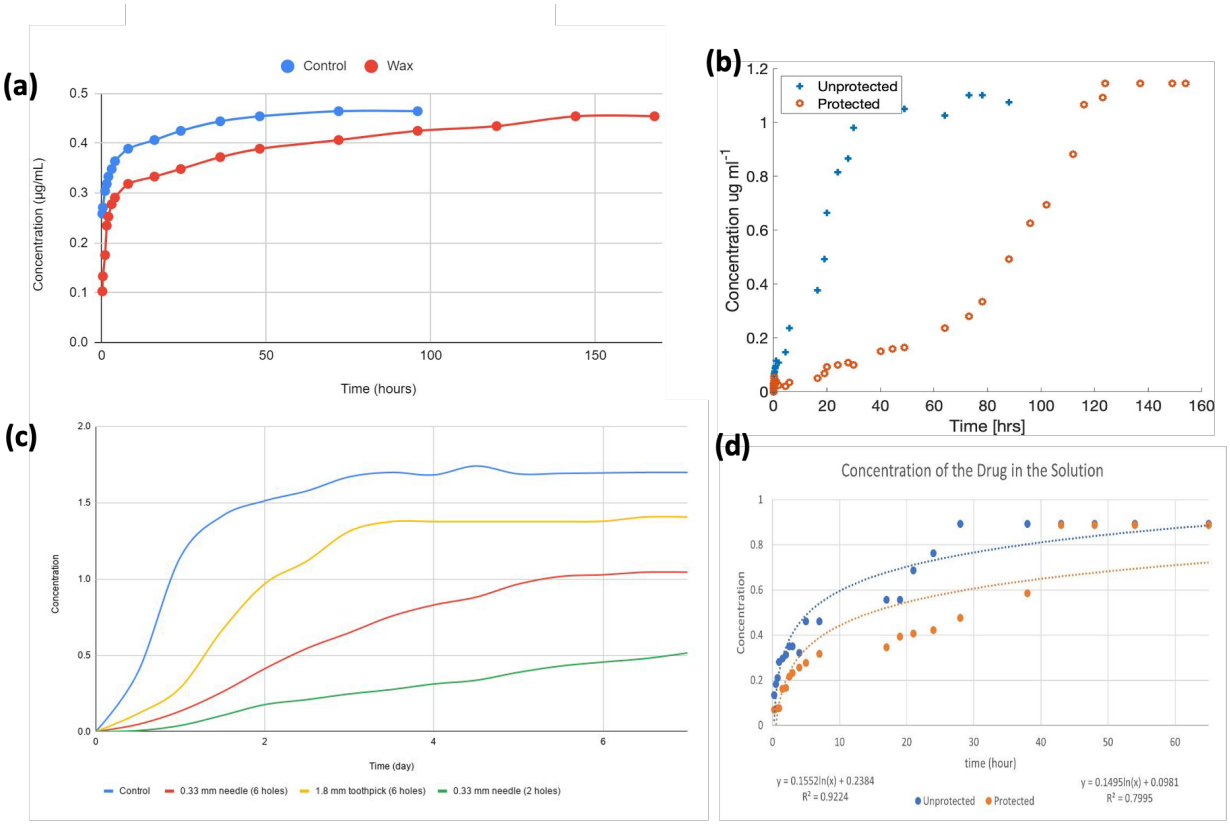

Figure 8. Example of students' works on the release profile over time. The blue dots/lines in all four panels that were labeled as control are the data from the potato cubes (core). Lines with other colors are from the core-shell structures (protected with a secondary layer of shell materials either wax or materials of students' choice). Figure (c) also investigated effect of water contact by making holes of different sizes into the wax-shell.

Lastly, Figure 9 shows two representative examples of students' work where students compared the experimental data with classic Fickian diffusion in Figure 9(a), while the other figure shows the concentration in the immediate vicinity (i.e. peripheral compartments) for an ibuprofen pill using the kinetic data reported in the literature for a two-compartment model system.

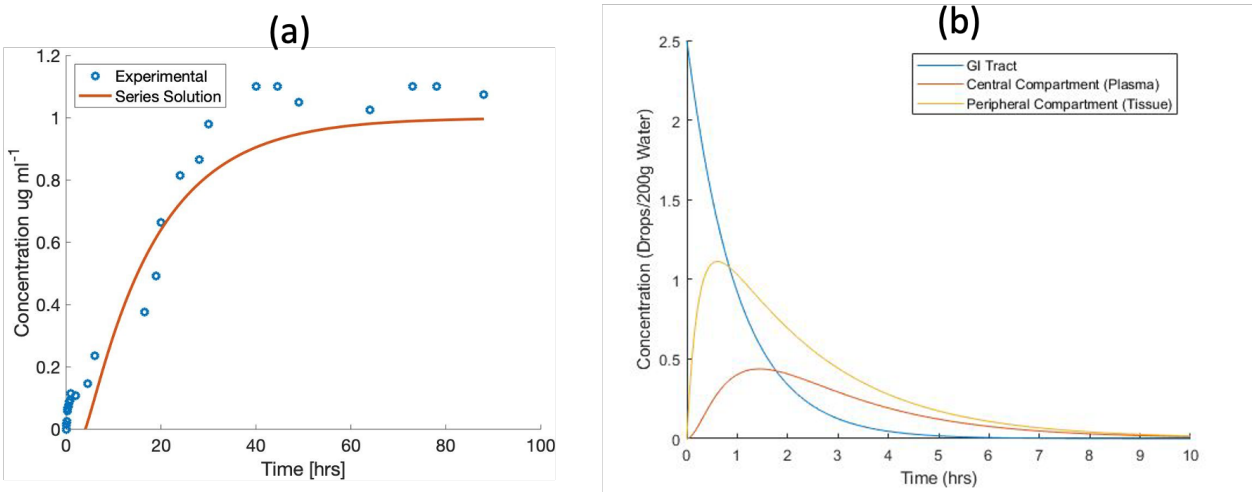

Figure 9. (a) example of students' works on the dye released over time that was fit to a Fickian diffusion model, (b) result of a 2-compartment model using kinetic data reported in the literature.

Students were successful in achieving most of the learning objectives for this experiment as shown in **Table 2**. About 90% students were appropriately set up the experiment i.e. choosing right materials, set up a DIY spectrometer, collected the data, and analyzed them. The average experimental data and trend that were reported was generally acceptable within some variabilities. In fact, the variabilities indicated the practicality of the at-home experiment and ability of the students to build their own experiment. Students, however, needed feedback on data presentation and analysis. Students also generally needed help to fit the data with a theoretical model, with MATLAB and the two-compartment model.

From a practical standpoint, sending kits to home was logistically challenging that required significant work from the faculty and staff. Combining the logistical issues with the similar student outcomes achievement that we have seen in the in-person labs, this experiment was a success. In fact, motivated by the successful outcome, the instructor designed an alginate based in-person drug delivery experiment [15] and offered in Fall 2022 semester.

Table 2. Summary of the students works evaluated and outcomes achieved

Tasks	Skills demonstrated	% of students achieving the outcome (N = 43)
If students were able to:		
Summarize the problem into research question(s)	**Synthesis.** Relate knowledge from several areas i.e. compose, combine, create	79%
Design the experiment in steps, at least identify variables to be manipulated and responding variables.	**Evaluation.** Making choices based upon reasoned arguments	89%
Predict the behavior and/or have hypothesis	**Synthesis.** Relate knowledge from several areas i.e. compose, combine, create	93%
Collect and organize the data in table(s) that is logical and understandable	**Analysis.** Organization of parts. Identification of components. (order, classify, arrange)	93%
Plot the data that clearly depicts the summary of the experiment	**Analysis.** Organization of parts. Identification of components. (Order, classify, arrange)	86%
Compare with the theoretical models with experimental observation	**Evaluation.** Verify the results. Use of modern tools, understand the broader impact	72%
Explains how the data and graph supports or refutes the prediction. Make recommendation for future experiment	**Create.** Make choices based upon reasoned argument. (Assess, select, judge, summarize, compare and recommend)	67%

Conclusion

The at-home drug-delivery experiment was largely successful in achieving the learning objectives and engaging the students in hands-on studies to augment their theoretical learning. The results and analysis that the students presented were very satisfactory considering the experiment was built solely on the household items and a smart phone. The experiment had almost no logistical issues. Due to its success, the instructor has developed and offered an in-

person drug delivery experiment based on the alginate chemistry in Fall 2022 semester. The author is also undertaking a project on using the at-home experiment platform to teach other critically important ABET Student Outcomes such as critical thinking skills.

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