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Laboratory Experiment

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Microbeads and Engineering Design in Chemistry: No Small Educational Investigation

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S Supporting Information

ABSTRACT: A multipart laboratory activity introducing microbeads was created to meet engineering and engineering design practices consistent with new Next Generation Science Standards (NGSS). Microbeads are a current topic of concern as they have been found to cause adverse impacts in both marine and freshwater systems resulting in multiple states proposing or adopting legislation to ban their manufacture or sale. The activity allows for student inquiry, discovery, and engineering design using inexpensive, readily available, and safe chemicals. In addition, the products tested (toothpastes, facial-cleansers, and/or hand-cleansers) will be familiar items to the students, stressing the ubiquitous nature of chemistry. The activity fostered confidence in the students through designing and testing procedures, introduced them to a topic that most knew nothing about, and drew praise for achieving the learning goals while investigating a relevant real-world problem.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Environmental Chemistry, Hands-On Learning/Manipulatives, Problem Solving/Decision Making, Microscale Lab, Water/Water Chemistry, Laboratory Instruction, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning*

■ INTRODUCTION

Since mass production began in the late 1940s, the amount of plastic in the environment has gradually increased to levels in which plastic pollution is regarded as the most prevalent form of anthropogenic pollution in marine environments accounting for an estimated $13 billion dollars of damage.[1,2] In the 1970s, masses of floating plastics found in oceanic gyres were identified and found to consist of large pieces of macroplastics (>5 mm). In subsequent years, attention turned to microplastics (<5 mm). Microbeads, a subset of microplastics, are important components in personal care products including many toothpastes, hand-cleansers, and facial-cleansers.

The small size of microbeads results in high surface area to volume ratios and is an important factor in how they interact with organic contaminants. Microbeads in personal care products are organic polymers of polyethylene and or polypropylene. Polyethylene is also utilized in passive diffusive samplers for detecting hydrophobic organic compounds such as polychlorinated biphenyls (PCB) and poly aromatic hydrocarbons (PAH) in aquatic environments.[3] The partitioning coefficients and surface chemistry interactions between polyethylene and these aquatic contaminants have been investigated in varying environmental conditions.[4]

The presence of microbeads has increased in soaps and scrubs to the point that now many consumers use compounds with microbeads on a regular basis.[5] Microbeads pose a problem in aquatic systems as they can be ingested by aquatic organisms, affect the food chain through bioaccumulation, act as binding agents for persistent organic compounds, act as vectors for diseases and invasive species, and can cause injury or death to the ingesting organisms.[1,6,7] Initially detected in marine systems, recent sampling efforts have found microbeads in freshwater ecosystems as well.[8−10]

The potential downside of microbeads has resulted in both national and international organizations calling for a restriction in their use. Many manufacturers have agreed to phase microbeads out in the near future and numerous states, including New York, California, and Illinois, have either passed or proposed laws banning the manufacturing and distribution of microbeads in personal care products.

As change swirls around microbeads, change also swirls around science curriculums in the form of the Next Generation Science Standards (NGSS). Published in 2013, the NGSS represent decades of efforts and the most comprehensive overhaul of our country's science curriculum since the post-Sputnik era and will require important improvements in all educational levels, K-20.[11−14]

The NGSS are composed of three-dimensions: Cross-cutting Concepts, Disciplinary Core Ideas, and the Practices.[15] Engineering and engineering design practices, entailing iterative cycles of design, analysis, and redesign, are the biggest changes for most state standards, yet as they are all tied to constructivist theories, they are a good fit for problem-based and project-based learning.[16,17] Scientific inquiry and engineering design are related and often integrated, but they are not the same.[18,19] Scientific inquiry seeks to translate what is observed into symbols, or questions, while engineering design translates them into phenomena or products (Figure 1).[20]

In a comprehensive review of more than 112 unique studies of the challenges for new science teachers published in 2006, there was no mention of engineering design.[21] This does not

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Scientific Inquiry	Engineering Design
• Observe/question a phenomena. • Develop a researchable question. • Conduct a literature search. • Propose a hypothesis. • Select a research design. • Plan the methodological details and procedure. • Conduct the investigation and collect data. Revisit procedure as needed. • Analyze and display data. • Interpret findings. • Draw conclusions and revisit the hypothesis. • Discuss findings and state implications for future research. • Communicate results.	• Identify/Recognize a need. • Define the problem. • Articulate the design constraints. • Gather information from a literature search or from pilot observations. • Revise the problem statement based on the new information. • Brainstorm possible solutions. • Choose a course of actions based on the available resources. • Create a prototype(s) or model(s). • Test and assess each prototype/model. • Evaluate and optimize the possible solutions. • Communicate results.

Figure 1. Comparison of both the steps of scientific inquiry and engineering design.[18]

mean that engineering design presents little if any challenges. An important question was asked by Lederman and Lederman,[22] "How much engineering background will science teacher educators need and where will they get it?" Related observations were made by Padilla and Cooper,[16] "If teachers are to be prepared to use the NGSS, the science curriculum that potential teachers take must radically change," and Talanquer and Sevian,[23] "Our future depends on an informed citizenry that makes responsible decisions and executes deliberate action based on chemical thinking about properties of classes of substances and chemical processes." In response to such statements, this chemistry activity was designed to incorporate engineering design practices to appeal to high school educators needing to meet the new standards and college professors who are training the next generation of science teachers.

We have somewhat artificially separated the scientific background activities from the engineering design challenge in the hope that both will be clear for the reader. That does not mean, however, that they need to be taught that way. The activities described in this article are meant to be highly adaptable. An instructor may choose to do a subset of the activities as a 1 h lab, all aspects in multiple 3 h sessions, or even assign them as independent or group projects to be done outside of standard lab times. One might choose the activities to support learning objectives in a high school chemistry course, or college general chemistry, environmental chemistry, materials chemistry, or nonmajors chemistry courses. The activities described can be used in a classroom setting, as extracurricular enrichment, or as outreach activities. Our aim is to provide adaptable activities for a creative instructor to utilize in a variety of settings.

The organization of the article is to first present activities that delineate the scientific underpinnings of microbeads, followed by some methodologies to incorporate engineering design practices with a microbead investigation. Results of surveying and assessing our students will be presented last, with some final discussion and conclusions.

■ LABORATORY ACTIVITY OVERVIEW

Microbead Physical and Chemical Characterization

Filter a small (<0.1 g) amount of microbead containing sample (e.g., face scrub, tooth paste, etc. labeled as containing polyethylene and/or polypropylene) through a coffee filter. Several solutions are capable of dissolving the associated material surrounding the microbeads. A 50:50 (v/v) solution of isopropyl alcohol was found to work well in isolating the microbeads on the filter paper. Air or oven dry the filter to complete the isolation of the microbeads.

To gain an approximation of the size range of the microbeads, filter a small (<0.1 g) sample through three sizes of preweighed filter paper, 50 μm, 100 μm, and 500 μm. To determine the mass of the microbeads as a fraction or percentage of the mass of the original sample, rinse the filter paper with 50:50 (v/v) solution of isopropyl alcohol, let the filter air-dry, remass the filter paper, and calculate the mass of microbeads by difference. Lastly, a more accurate size measurement can be taken by placing the dried microbeads under a dissecting microscope and measuring them with a microscale ruler.

Another important chemical characteristic of microbeads—the propensity of solvents or compounds to adhere to the microbeads—can be explored using coffee. This can be used to teach a variety of topics ranging from polar/nonpolar molecules, to surface adhesion, to chemical reactivity. As many microbeads are made of polyethylene, the absorption of a nonpolar solvent would be interesting, but many of those solvents present problems in disposal and might also dissolve the microbeads. These same nonpolar solvents generally have high vapor pressures; thus, students trying to measure the mass of a small amount of the solvent absorbed on the microbead would be challenged with hitting a moving target as the solvent evaporated.

Students found that coffee was a solvent that was easy to measure. Students place a sample of microbeads on a 100 μm premassed filter and no microbeads on a control filter. They add 3 drops (~0.15 mL) of coffee to each filter paper and let it set for 5 min. At the end of 5 min, they mass each filter. From this information, students determine the mass of the beads, the mass of the liquid coffee that adheres to the filter (no microbeads), and the mass of coffee that adheres to the filter with the microbeads. By subtracting the last two values, students determine the mass of coffee absorbed onto the microbeads. The ratio of mass of coffee (absorbed onto the microbeads) to the mass of microbeads can be calculated and deviations determined by having students measuring in triplicate or combining class data. Water or another solvent's interaction with the microbeads and filter can easily be tested in the same way and can serve as a comparison.

Microbead Engineering Design Challenge

In the prelab assignment, the students are tasked with conducting an independent literature search on the issue of

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microbeads. They are to come up with a statement of the overall problem and are given a goal of finding five or more facets of the overall problem to bring to class. Pursuing information on microbeads is an effort that most students can handle deftly, and this background is important for establishing the foundation of the activity as well as its relevancy to the course and student.

It is likely that many students will have had little or no experience with engineering design practices, so it may be wise to formally address key aspects (defining solutions, designing solutions, and optimizing solutions), as one leads the activity. Ask students to offer their impressions of facets of the problems of microbeads and place these suggestions on the board, screen, discussion forum, etc. Explain to the students that each one of these facets can be thought of as a mini-problem whose solution begins to solve the overall problem associated with microbeads. Advise them that their research group can choose any portion of the problem to work on. At this point each group should develop a problem statement and then brainstorm possible ideas to solve the problem. An example of this might proceed as follows:

Students would determine a mini-problem statement, such as Microbeads pass unchanged through sewage treatment systems. A possible design solution would be to add a flocculant to precipitate microbeads. Delimiting this problem (determining design constraints, and evaluation criteria) might include:

- This process should be capable of being used at a central facility
- The flocculant must be nontoxic
- The process should induce flocculation in a reasonable time period (<15 min)
- The process should create flocs that can be removed with existing settling/filtration systems
- Flocculant additive must be cost-effective

Student teams would research various flocculating additives and determine a procedure that would test amounts and mechanisms against the criteria above. Teams discuss the procedure with the instructor as a check for availability of materials and to alleviate any safety concerns. After this final instructor approval, the students carry out their series of activities, testing and optimizing their design solution. Students are creative and unique, and it is likely they will provide a range of many possible design solutions. Students might investigate replacing the microbead with biodegradable material by determining how physical characteristics varied between the materials (Table 1). Multiple groups in one class chose to analyze different scrubs to determine microbead differences between different products, while another group examined the size distribution of various microbeads before and after heating (Figure 2). Other groups tried to dissolve the beads with various solvents, while others added flocculating agents to mixtures containing microbeads.

Table 1. Physical Characteristics of Microbeads and Potential Microbead Replacements As Measured by Students

Compound	Diameter (cm)	Surface Area (cm^2)	Volume (cm^3)	Surface Area/Volume
Microbeads	4.1×10^{-3}	5.2×10^{-5}	3.5×10^{-8}	1.5×10^{3}
Sand	4.0×10^{-2}	5.0×10^{-3}	3.4×10^{-5}	1.5×10^{2}
Oats	6.0×10^{-2}	1.1×10^{-2}	1.1×10^{-4}	1.0×10^{2}

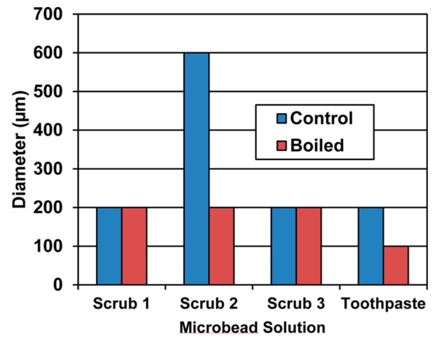

Figure 2. Change in microbead particle size after student manipulation (boiling) to determine how heating influences filtering efficiency.

Optimizing the Solution and Communicating the Results

The summative evaluation of this activity is adaptable, although a final written lab report and team presentation works well. Depending on logistical constraints, this can be a brief in-class discussion, or it can go so far as to another round of brainstorming followed by testing improved design solutions. An intermediate way to teach optimizing solutions is to have the students present their findings, then have student teams add a section to their lab reports, "The Next Step". The "Next Step" could be a paragraph or two on what they would do next and their rationale for that course of action.

■ HAZARDS

In the course of this activity, students should wear protective eyewear. If isopropyl alcohol or another similarly flammable liquid is used to rinse the microbeads, appropriate protective measures should be taken including ensuring students wear gloves and that no open flames are present. Note that the procedures the students develop may call for chemicals needing special precautions and should be dealt with on a case by case basis and should be included in a hazards section of their procedure and noted in their final reports.

■ DISCUSSION

Researchers have identified the need for the education of the public regarding the threat of microbeads as both immediate and long-term threats to the health of marine environments.[5] This activity was very effective in not only alerting the students of a problem they previously did not know existed, but also in making them aware of microbeads (most students began the activity with no knowledge of microbeads whatsoever). Assessments were done with pre- and post-tests to determine content knowledge and retention of the materials presented in the activity and a student assessment of learning gains (SALG) survey was administered to gauge the students' feelings about the activity and to measure learning gains resulting from this activity. One hundred percent of the students in the SALG survey indicated the lab allowed them to make good or great gains in understanding the environmental impact of microbeads. Figure 3 shows that students demonstrated an increase in their understanding of microbeads and engineering design practices.

Many students commented on the practical nature of the lab activity, and a significant number of students included observations related to specific aspects of engineering design:

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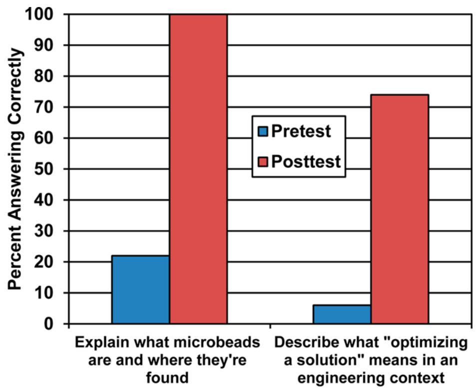

Figure 3. Percent of students answering correctly on quiz questions taken before (pretest) and after (posttest) completing the activity (n = 32 and 27, respectively).

> *I literally knew nothing about microbeads, their makeup, or the impact they had on the environment. I am now well-educated on all of the above subjects.*
>
> *I'm typically not one to enjoy chemistry labs, but this lab really showed me that in real life, outside of the classroom, chemistry is very independent and an individual can design, engineer, and focus on whatever they like. Instead of simply following a procedure, we can create our own, and that was enjoyable to me.*
>
> *I was really able to relate this to the current day, and come up with relevant ways to solve a problem that would be realistic in the real world in relation to a realistic product along with its marketability.*
>
> *I've learned the whole process engineers have to go through and how many times they may fail, but keep trying and learning from each fault.*

The skills the students learned from this activity were investigated to ensure that the learning objectives were being met. Figure 4 shows the results of student self-assessments, via the SALG survey, indicating they gained a wide range of skills from this activity. Perhaps most importantly this lab also impacted the students' views on chemistry and research. Over 60% of students indicated this activity increased their enthusiasm for chemistry, and nearly 70% of all students indicated this activity gave them the confidence to design a project using engineering design and now had interest in doing their own research project as an undergraduate student. Previous research have shown that engineering design projects help to develop a greater sense of the purposes and goals of chemistry and engineering, which can clarify future careers and can lead to greater skills in leadership, communication, and collaboration.[24] In summary, this activity allows for student inquiry, discovery, and engineering design using inexpensive, readily available, and safe chemicals. The experience gave the students confidence in designing and testing procedures, introduced them to a topic that most knew nothing about, and drew praise for achieving the learning goals while investigating a relevant real-world problem.

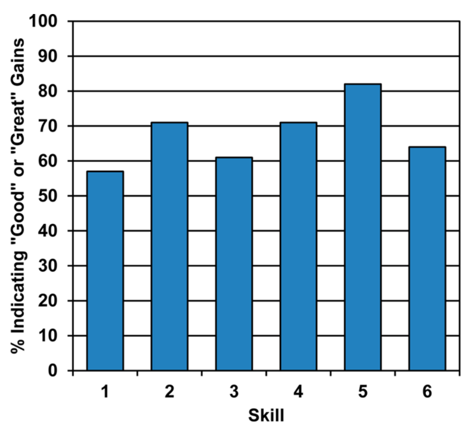

Figure 4. Percent of students that reported that this activity allowed them to make "good" or "great" gains in the following skills: Skill 1, Finding articles/information relevant to a particular problem in professional journals or elsewhere; Skill 2, Developing a engineering test procedure; Skill 3, Preparing and giving oral presentations; Skill 4, Working effectively with others; Skill 5, Investigating a real world problem; and Skill 6, Writing a lab report in using appropriate style and format (n = 28).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Full procedure, data tables, microscale ruler, rubric, and notes for the instructor, including background articles and links. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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