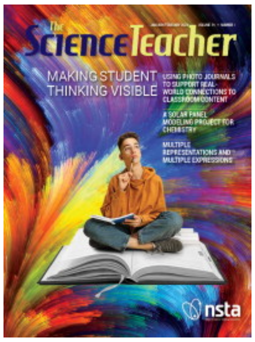

The Science Teacher

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/utst20

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To cite this article: Elizabeth Vicario, Rita Ortiz, Kofi Acheaw Owusu, Allan Feldman, Kebreab Ghebremichael & Sarina J. Ergas (2024) Engaging Students in Waste-to-Energy Research Using Model Biodigesters, The Science Teacher, 91:1, 22-30, DOI: 10.1080/00368555.2023.2292331

To link to this article: https://doi.org/10.1080/00368555.2023.2292331

Engaging Students in Waste-to-Energy Research Using Model Biodigesters

ELIZABETH VICARIO, RITA ORTIZ, KOFI ACHEAW OWUSU, ALLAN FELDMAN, KEBREAB GHEBREMICHAEL, AND SARINA J. ERGAS

ABSTRACT

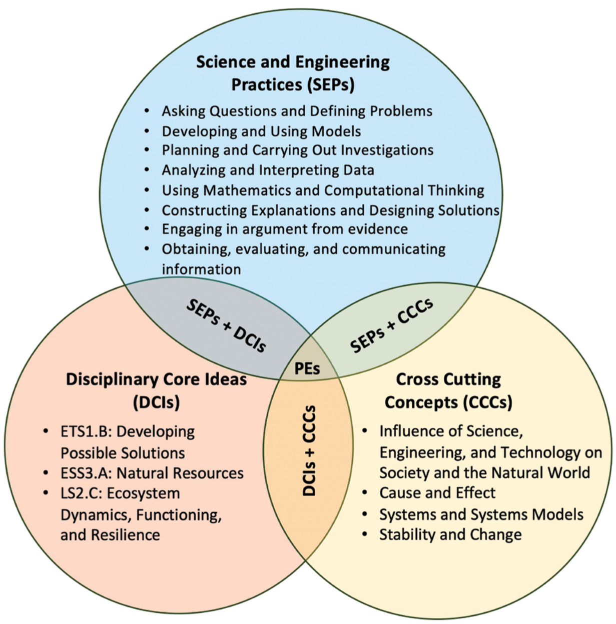
Anaerobic digestion (AD) is a natural process whereby microorganisms break down organic material in the absence of oxygen. Biodigesters (sealed tanks where AD occurs) are complex ecological systems where different microorganisms work together to produce biogas (a mixture of methane and carbon dioxide). They are used to produce energy and fertilizers from organic wastes, such as food waste, crop residues, and animal manure. This article describes the use of simple model biodigesters, built from low-cost or repurposed materials, as a way to introduce students to physical and conceptual models while learning about resource recovery, waste management and sustainability. This article provides an overview of how teachers can implement this in their science classrooms to engage students in science and engineering practices (SEPs). When used in schools in Ghana and the US, students learned about AD, developed research questions, and built a model biodigester as a tool for scientific inquiry. They collected and analyzed data (e.g., daily biogas and methane production), and they interpreted their results to answer their research questions and make recommendations for local biodigester construction. More complete information about engaging students in authentic science using biodigesters is available on our website.

Keywords: Science and engineering practices; authentic science; Ghanaian science education; anaerobic biodigesters; science education; science teaching; environmental education

Scientists and engineers use models to represent real-world phenomena, design and understand complex systems, and ask "what if" questions (Khandan, 2002; Feldman, Cooke, & Ellsworth, 2010). In this article, we present a way for students to investigate biological waste-to-energy technologies using model anaerobic biodigesters. Through this project, students learn to use models as scientific tools to ask questions, carry out investigations, and develop solutions to problems in their communities as described in the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013). Student investigations using the model biodigesters allows for them to engage in sensemaking of a wide range of science topics in biology and chemistry, including the role of microorganisms in biological decomposition; the chemistry needed to determine the amount of methane produced; and environmental and ecological issues related to the use of biodigesters in the food-energy-water nexus (Stephan et al., 2018). In particular, as shown in Figure 1, students explore high school level science and engineering practices (SEPs), disciplinary core ideas (DCIs) and cross-cutting concepts (CCCs) from the *NGSS*.

FIGURE 1

The biodigester project has students engage in all eight SEPs. The DCIs and CCCs are specific to the project. The PEs are included in the table "Connecting to the Next Generation Science Standards."



Anaerobic digestion (AD) is a biological process that can be used to convert organic wastes into energy and fertilizer (USEPA, 2015; Moussa, 2022). Biology teachers can use AD to teach about biochemical processes, while environmental science, engineering, and technology teachers may focus on real-world waste-to-energy applications. One science teacher connected the topic to food waste, lack of landfill space, and climate change. Another science teacher in St. Petersburg, FL related the topic to life on Mars by explaining how energy could be produced while treating human waste. In Cape Coast, Ghana, we linked the topic to the use of firewood in the school kitchen, which was contributing to deforestation and air pollution.

Biodigesters

AD can be harnessed in a biodigester, which is a sealed anaerobic tank that has inlets for feedstock and outlets for digestate and biogas (Figure 2). Feedstocks can include organic waste materials, such as food waste, livestock manure, sewage sludge, yard waste and crop residues (Hinds, Lens, Zhang, & Ergas, 2017). Biodigesters produce biogas

FIGURE 2

What goes in and what comes out of a biodigester?

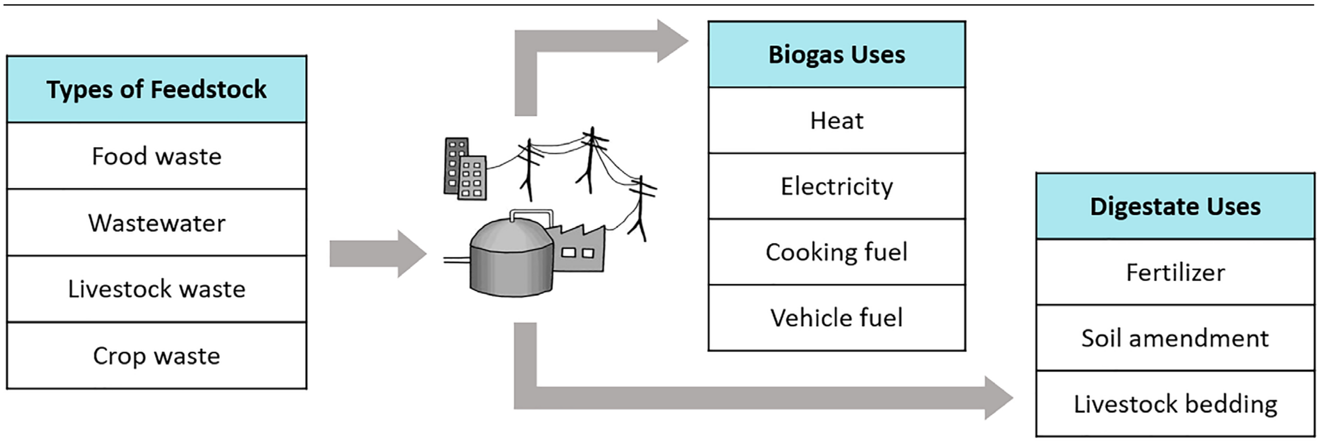


TABLE 1

Advantages of biodigesters and their applications.

Biogas is a useful product	Biogas is a renewable energy source that can be used for cooking, heating, vehicle fuel, or electricity generation. Biogas is cleaner than fossil fuels or firewood, which contribute to climate change, deforestation and air pollution.
Digestate is a useful product	Digestate is a nutrient-rich liquid that can be applied to soil without causing odors, attracting pests, or spreading disease. Using digestate as fertilizer reduces the energy costs and environmental damage of synthetic fertilizers.
Turns wastes into resources	Anaerobic digestion feedstocks include human waste (e.g., sewage sludge), animal manure, crop residues (e.g., corn stalks), industrial waste (e.g., from food processing), food waste, and yard waste.
Can be applied at different scales	Waste from a small farm can be treated in simple biodigesters and the biogas can be piped to a cook stove to be burned as cooking fuel. Industrial systems at large farms or wastewater treatment plants use more complex technology to generate heat, electricity, or vehicle fuel.
Reduces wastes going to landfills	When organic waste decomposes in a landfill, methane is released into the atmosphere. Methane is a powerful greenhouse gas that contributes to global climate change and has value as an energy source.

FIGURE 3

Schematic of a model biodigester.

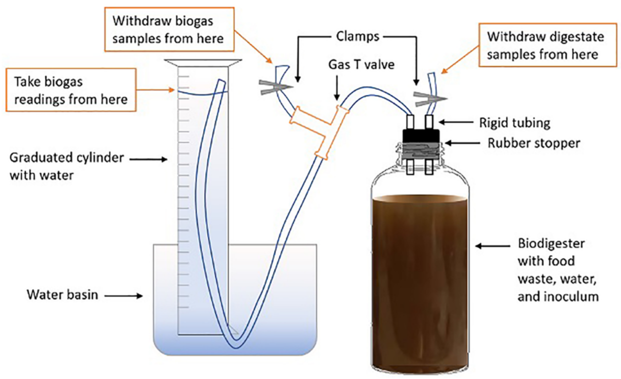


FIGURE 4

Photograph of the model biodigester.

and digestate. Biogas is a mixture of methane (CH_4) and carbon dioxide (CO_2) that can be processed into vehicle fuel, burned directly for heating or cooking, or used to generate electricity. Digestate, the liquid effluent from the biodigester, can be used as a nutrient-rich fertilizer. Biodigesters have many advantages (Table 1) and are used around the world at different scales.

AD and model biodigesters in the classroom

We developed a model biodigester (see Figures 3 and 4) students can use to learn about the science of AD and answer research questions about how different conditions or designs might affect the AD process. We piloted the model with middle

TABLE 2

Suggested timetable for the curriculum and estimates of required class time.

Week	Tasks	Percent of class time
1	Introduction to the science of AD and biodigesters Developing research questions Materials collection and model building	100%
2	Data collection Daily biogas measurements (5 minutes) Twice-weekly methane measurements (10-15 minutes) Twice-weekly pH measurements (5-10 minutes)	10-30%
3	Data collection	10-30%
4	Additional data collection until biogas production has ended	10-30%
5	Data analysis and interpretation Communication of results through poster and presentation	100%

FIGURE 5

Steps in the AD process. All steps occur simultaneously in a healthy biodigester.

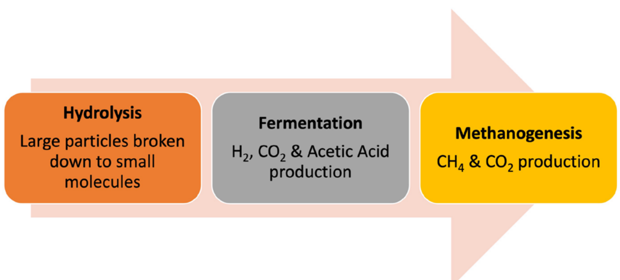
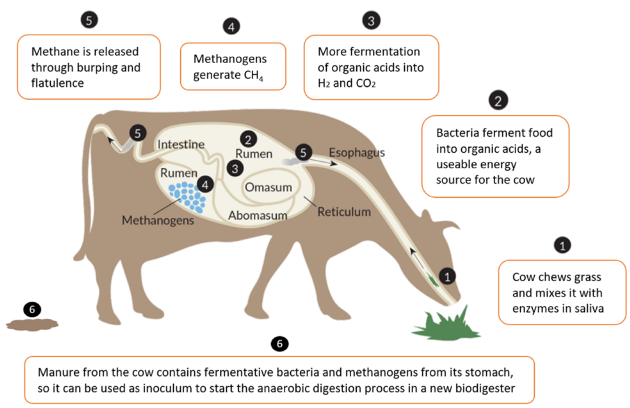


FIGURE 6

A cow's digestive system as a conceptual model of a biodigester (modified from Beil, (2015)).



school students and undergraduate science education students in the United States, and implemented it in a high school in Cape Coast. Supplies for the biodigester are inexpensive and readily available, and the curriculum materials and laboratory procedures are available on our website (see Online Resources). We recommend allotting five weeks for the activity, as outlined in Table 2. Most of the class time is needed at the beginning and the end of the project. When the biodigesters are operating, class time is only needed to collect data and make observations.

Introduction to the science of anaerobic digestion

In AD, microorganisms break down organic matter in the absence of oxygen in several steps (Figure 5). During *hydrolysis*, organic particles are broken down into smaller molecules, such as proteins and carbohydrates. During *fermentation*, these molecules are further broken down into hydrogen gas (H_2), carbon dioxide (CO_2) and organic acids, such as acetic acid (the acid in vinegar). Fermentation may be familiar to students because it is used to make products like bread, yogurt, and cheese. The yeast in bread dough converts sugars and starch into ethanol and carbon dioxide, releasing gas bubbles in the dough and causing it to rise. *Methanogenesis,* the production of methane, is carried out by microorganisms called methanogens. Methanogens belong to the archaea domain and are found in extreme environments like wetlands, the sea floor, and the stomachs of ruminant animals (e.g., cows and goats). They use end products from the fermentation step to produce methane (CH_4).

The digestive process of a ruminant is a useful conceptual model of a biodigester (Figure 6). When a cow eats grass, the grass

FIGURE 7

Setting up the gas collection system at a school in Cape Coast, Ghana.

is broken down by chewing and mixing with enzymes in saliva, which is similar to chopping the feedstock for the biodigester. The partly digested food, or cud, travels to the rumen, which, like a biodigester, is a chamber full of anaerobic microbes (Orr, 2011). The microbes produce organic acids, which are the main source of nutrition for the cow. Methane is produced as a by-product of the cow's digestion and is released in the animal's belches and flatulence, which contributes to greenhouse gas emissions (USDA, 2022). Farmers can reduce greenhouse gas emissions from cattle through better breeding, nutrition, and waste management practices (Knapp et al., 2014), such as by using AD to recover energy from animal manure (USEPA, 2015).

Inoculum materials, advantages and disadvantages

Biodigesters need to contain the proper microbes, or microbiome, for AD to occur. A good inoculum source can enhance biodegradability, shorten the lag time before methane is produced, and help prevent souring (Rajput and Sheikh, 2019). One of the following inoculum materials can be used in the model biodigester:

- **Manure from a cow, sheep or goat:** the rumen is a chamber full of microbes. Therefore, ruminant manure has of all the microbes needed in the AD process. Ruminant manure is available from farms, 4-H clubs, zoos, etc. However, animal manure can carry zoonotic diseases, such as Giardia. We recommend that only teachers handle manure and that they wear personal protective equipment (gloves, goggles, lab coat).
- **Anaerobically digested sewage sludge:** in many communities, wastewater treatment plants use AD to produce class A biosolids. According to the EPA, Class A biosolids are free of pathogens and can be used on home vegetable gardens. Be sure to explain to the treatment plant operators that you want the effluent from the anaerobic digester, which is a rich source of anaerobic microbes.
- **Anaerobic sediment:** sediment or soil dug from below the surface of an organic rich area, such as a wetland or garden, also contains a rich anaerobic microbiome (Mutschlechner et al., 2020). Using soil as an inoculum may require a little more time before methane production is observed.

Building the model biodigester

In this project students have the opportunity to learn the above science of AD through their investigations using the model biodigester. The model has two parts: the biodigester itself (on the right in Figure 3) and a gas collection system (on the left). For the biodigester, we used a clear plastic bottle and a well-fitting rubber stopper with two holes. Biogas travels through one of the holes to the gas collection system through flexible tubing. The second hole can be used to take samples of the digestate (liquid slurry in the bottle) to measure pH. At other times it should be plugged to keep the system anaerobic. To measure the methane content of the biogas, a T-connector and clamp needs to be inserted into the tubing to provide an access point. The gas collection system can be constructed from an upside-down graduated cylinder or manually calibrated cylinder (we used glass vases from a dollar store) and a plastic bowl or container. Figure 7 shows a student setting up the gas collection system.

Filling the biodigester

After the biodigester is built, inoculum and feedstock need to be added to it. We recommend a mixture of one part feedstock, one part inoculum, and two parts water. These materials need to be well mixed before adding them to the biodigester. This could be done in a gallon-size sealable plastic bag.

Inoculum

The inoculum is a mixture of microorganisms that includes bacteria and archaea capable of carrying out all the steps in the AD process (Figure 5). Available sources of inoculum include cow, sheep, or goat manure, anaerobically digested sludge from a wastewater treatment plant, or soil from an organic rich area, such as a wetland (see Box: Inoculum materials, advantages and disadvantages). If manure is used, safety precautions must be taken. We recommend that only teachers come into contact with it, and, along with the students, should use gloves, lab coats and safety glasses when handling manure or other animal products that could carry diseases.

The filling of the biodigesters is an opportune time for teachers to review with students the role of the microorganisms in the inoculum. This knowledge is important if they choose to modify these ratios, the type of inoculum source, or the feedstock to fit their research questions.

Feedstock

Feedstock is the organic material digested by the microorganisms. A wide variety of materials can be used, depending on the research questions that the students ask. The material needs to be chopped into small pieces so that there is a good mixing of it with the inoculum. If students use food waste from home, the school cafeteria, or from their own lunches, they can see directly how the use of biodigesters reduces the amount of garbage that goes into landfills.

Engaging in science and engineering practices (SEPs)

In this project, students use the model biodigester to pose and answer questions related to their use. In doing so, they engage in the SEPs described in *A Framework for K-12 Science Education* (National Research Council, 2012) and the *NGSS* (NGSS Lead States, 2013). We recommend that students work together in teams for this project because collaboration is an important part of how scientists and engineers engage in their practices. Our website has information and teaching materials related to each of the SEPs: https://www.usf.edu/nsf-ires/research.

Asking questions and planning investigations

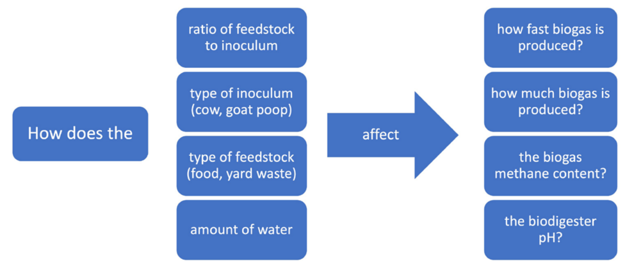
Many students struggle to come up with good research questions, but we have had success using a simple method (Alsultan et al., 2021). It frames a research question as: "How does A affect the B of C?" where A is the independent variable (to be manipulated), B is the dependent variable (to be measured) and C is the system being studied. Figure 8 shows some of the questions students asked. Students could also test variations in the biodigester design, its operating temperature, or other environmental conditions. To come up with good questions and plans, they need to understand the science of AD, including associated DCIs and CCCs. After agreeing on a research question, each group designs a lab protocol, with safety considerations, detailed assembly instructions, and a data collection plan. We recommend building two or three biodigesters per team, with one inoculum only control for the whole class.

Developing and using models

Students engage in this SEP throughout the activity. To highlight how their biodigester acts as a model, teachers can ask questions like "How is the experiment like and unlike AD in nature and in engineered systems?" "What are the limitations

FIGURE 8

Example model biodigester research questions.



of the model, and how could it be adapted to reflect different environments where AD occurs?" Tours of biodigesters may be available at a wastewater treatment plant near the school, and virtual tours can be found in Online Resources. Such tours or other external resources provide students with the opportunity to explore how people who operate biodigesters at a larger scale troubleshoot or problem solve.

Carrying out investigations

Data collection begins once the biodigesters have been set up. Biogas production is measured by reading the amount of gas collected in the calibrated cylinder. Initially, gas will accumulate rapidly as fermentation occurs, then level off after a few days, then rise again as methanogens become active.

The biogas is a mixture of methane and carbon dioxide. To determine the methane content, the carbon dioxide needs to be removed. One way to do this is to dissolve it in a basic solution. This can be done using a glass fermentation tube and a sodium hydroxide (lye) solution a (Figure 9). This is an opportunity for students to learn about the properties of carbon dioxide, why it dissolves in a basic solution, and can even be extended to climate

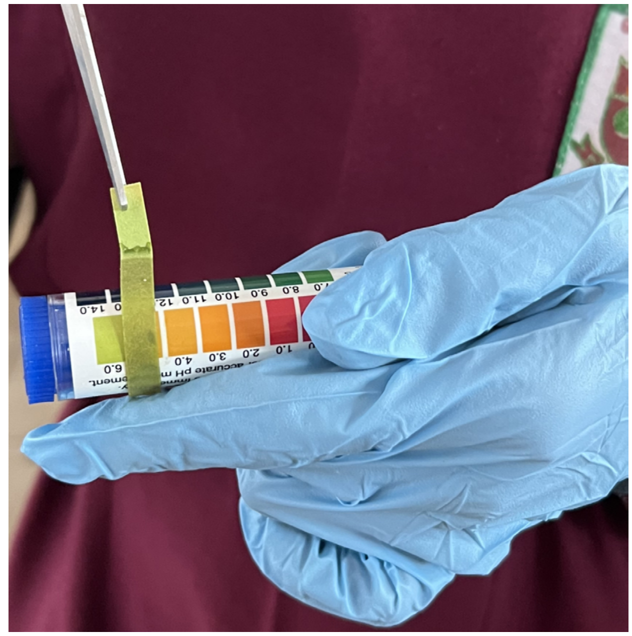
Large-scale biodigester (iStock).

FIGURE 9

Filling the fermentation tube with a base solution.

FIGURE 10

A student checking the pH of the digestate using pH paper.



change science through a discussion of how oceans serve as a carbon dioxide sink.

Because this measurement involves fragile glassware and a strong base (3 molar NaOH), extra safety precautions should be taken. A biogas sample is withdrawn (see Figure 3) and the gas is slowly injected into the fermentation tube. Carbon dioxide is absorbed into the solution while methane accumulates at the top of the tube. The biogas's methane content is calculated by dividing the methane volume by the total volume of biogas withdrawn.

To measure pH, students withdraw digestate samples with a syringe and test them with pH paper or a pH meter (Figure 10). Other measurements that can be taken easily are the temperature and mass of the biodigester. More detailed instructions are available on our website: https://www.usf.edu/nsf-ires/research.

Analyzing and interpreting data, and using mathematics and computational thinking

Each team should determine how they will record their data. For example, they can record daily and cumulative biogas production, pH of the digestate, and temperature and mass of the biodigester. The analysis of their data requires the students to engage in mathematical and computational thinking. For example, to calculate methane production they multiply the methane content (as a percent) by the daily biogas production. The team can then graph daily methane production for each biodigester and compare them using different measures, such as the number of days until methane production starts or the number of days until peak methane production occurs. For example, in analyzing their data the students may find that the biodigester "soured" or experienced a drop in pH and a reduction of methane production. Visual representations of the data can indicate when the biodigester began to sour, i.e., what day did the pH decline, and if this was the same time when methane production dropped.

Constructing explanations, designing solutions and communicating results

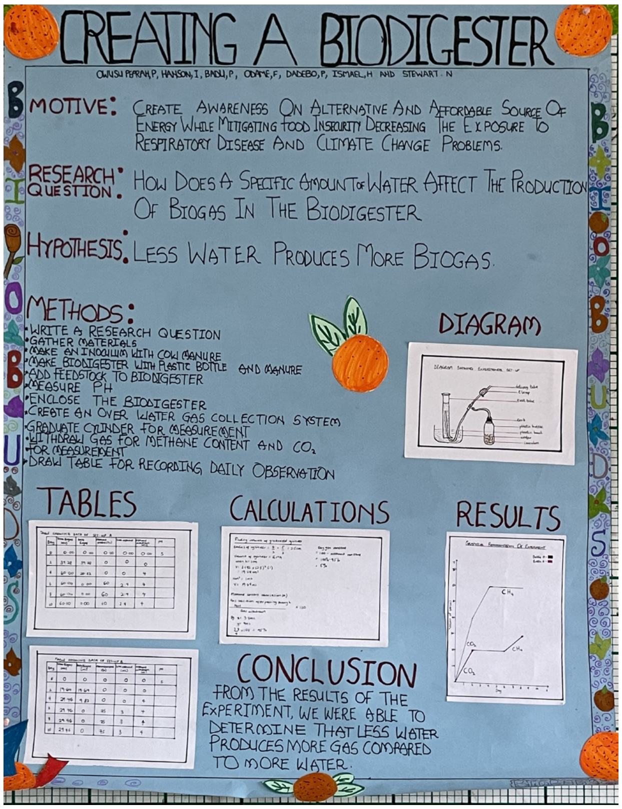
The biodigester activity leads to students engaging in all of these practices. In order for students to explain what they learned through their investigation; they will need to rely on the knowledge and understanding they gained about AD and how biodigesters work. In the example of the biodigester souring, students would need to use their knowledge of fermentation to explain what happened—when fermentation occurs faster than methanogenesis (Figure 5), organic acids will accumulate and lower the pH. A pH below 6 is toxic to methanogens and methane production will cease (the reactor sours). Low pH of the digestate and low methane production are evidence of this phenomenon.

Students can engage in the practice of designing solutions to find a way to prevent the bioreactor from souring. For example, a possible solution is to provide less feedstock and more inoculum. Students can compare biodigesters operated under different conditions as support to suggest the best conditions to prevent souring. Although each group should have the autonomy of creating their own research question, all groups could measure the pH of the digestate and the methane content of the biogas to help gather evidence to understand the phenomenon of biodigester souring.

The biodigester souring problem also illustrates the three-dimensional aspect of this project. From the above it should be clear how the students engage in the SEPs. A DCI connected to the souring problem is LS1.A: Structure and Function that

FIGURE 11

A student group's poster used to communicate their results.



includes the idea of feedback mechanisms, which is an example of the CCC Stability and Change. Being able to investigate why the souring occurred, is a PE for this set of SEPs, DCI, and CCC. A list of the SEPs, DCIs, and CCCs addressed in this project is found in the supplemental materials.

Another example of designing solutions is when students in Cape Coast investigated the feasibility of using a biodigester for their school. They interviewed kitchen staff to determine how much food waste was produced and estimated how much methane could be generated using a simple mathematical model. They then presented their explanations and solutions to peers, teachers, and administrators in posters (see Figure 11), which was how they communicated their results.

Students can also connect the use of biodigesters to local or global environmental issues related to waste management, food production, or energy production, i.e., the use of biodigesters as a solution to these problems. This also illustrates a three-dimensional aspect of this project. Connecting the use of the biodigesters to environmental issues addresses the DCI Interdependent Relationships in Ecosystems. They can then be evaluated on how they make use of the CCC Cause and Effect through the performance expectation of "Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity."

Conclusions

We saw that students were excited about the flexibility and open-endedness of the biodigester project. The inquiry approach made it easier for students to understand a complex biochemical process, and its connection to environmental problems. They gained familiarity with a variety of conceptual models (e.g., the cow figure, the experimental biodigester; and mathematical models), and used CCCs to explore natural phenomena. Students exceled at solving engineering challenges while building the biodigester, and the simplest solutions were usually the best (e.g., securing plastic graduated cylinders with tape so they did not wobble). However, it does require teachers to find time in already crowded curricula for this activity. But based on our preliminary analysis of interviews of students and teachers, the time can be well-worth it because students made connections to ideas like resource recovery, waste management, human health, climate change, and deforestation; and learned to engage in science and engineering practices.

SUPPLEMENTAL MATERIAL

Supplemental data for this article can be accessed online at http://dx.doi.org/10.1080/00368555.2023.2292331.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. OISE-1827132. The authors wish to acknowledge the 2022 participants of the NSF-IRES program in Ghana: Elizabeth Vicario, Erica Dasi, Mourin Jarin, Rita Ortiz, and Nicholas Stewart. The authors also wish to thank Ghanaian teachers Doris Osei-Antwi, Ishmael Yussef, Elijah Asare and the staff at Ghana National College (high school) for all the support and assistance they provided, and the University of Cape Coast for their support of the IRES program and its participants.

ONLINE RESOURCES

Project website with curriculum materials and instructions for building and using the model biodigesters: https://www.usf.edu/nsf-ires/research/

American Biogas Council: https://americanbiogascouncil.org/

UF IFAS Extension: https://biogas.ifas.ufl.edu/biogas/index.asp

Virtual Tour of on-farm AD system in Middlebury Vermont https://youtu.be/TYozO4Ded6U

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