Maximizing the Production of Biogas in an Instructional Manipulative Designed to Teach Energy Concepts to High School Students

by

Shakira Renee McCall

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Graduate Supervisory Committee:

Odesma Dalrymple, Chair
Bradley Rogers
Kiril Hristovski

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ABSTRACT

In an effort to stress the benefits of the application of renewable energy to the next generation of science, technology, engineering, arts, and mathematics (STEAM) professionals, instructional modules on energy and biogas were integrated into a summer camp curriculum that challenged students to apply STEAM concepts in the design and development of chain reaction machines. Each module comprised an interactive presentations and a hands-on component where students operated a manipulative relevant to the content. During summer 2013, this camp was implemented at two high schools in Arizona and one in Trinidad and Tobago. Assessments showed that the overall modules were effective in helping students learn and retain the information presented on energy and biogas production. To improve future implementations of these modules, specifically the module on biogas production, the anaerobic digester was redesigned. In addition, a designed experiment was conducted to determine how to optimize the influent and operational environment that is available in an average high school classroom to generate maximum biogas yield. Eight plug-flow anaerobic digesters made of PVC piping and fixtures were used in a 2^3 factorial design assessing: co-digestion (20mL or 50mL) used cooking oil, temperature (25°C or 40°C), and addition of inoculum (0mL or 200mL). Biogas production was captured at two intervals over a 30-day period, and the experiments were replicated three times. Results showed that temperature at 40°C significantly increased biogas production and should be used over 25°C when using anaerobic digesters. Other factors that may potentially increase biogas production are combination of temperature at 40°C and 50mL of used cooking oil. In the future, the improvements made in the design of the anaerobic digester, and the applications of the

finding from the experimental design, are expected to lead to an improved manipulative for teaching students about biogas production.

DEDICATION

To my Mother and Father

ACKNOWLEDGMENTS

First and foremost I thank God for his continuous protection and giving me the ability to live out my dreams.

I owe my gratitude to my parents, Andrew and Patricia McCall for being instrumental in molding me into the woman that I am today. They have done a wonderful job teaching me to celebrate my successes and leverage my failures for learning opportunities. Most of all, I am thankful for their continued faith in me and constant reminders that I can do can do ALL things through Christ who strengthens me.

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INTRODUCTION

Background

Energy is a part of life; it is the driving force for the environment, economics, technology, and overall human existence [1]. For example: The environment has a natural cycle between predator and prey. The prey is an energy source to the predator [2]. From cars to agriculture, fossil fuel to water heating, energy drives the economy [3]. Technology and the advancement of technology also rely on energy sources [4]. "The brain uses more energy than any other human organ [5]." These are just a few facts that prove without energy, life could not be possible. Consequently, energy should not just be considered a science, technology, engineering, and mathematics (STEM) topic; it is foundational, and should be part of our general knowledge.

Unfortunately, there are many misconceptions about energy and related concepts that can lead to poor decision-making concerning the usage of energy and misunderstandings of the planetary challenges related to energy [6]. Primary and secondary school students are often mislead and learn the following [7]:

- Energy degradation means decreasing in quantity
- Energy degradation is the opposite to energy conservation
- Energy conservation means saving
- Energy is used up or lost
- Global warming [is] associated with skin cancer
- Energy is stored in food and fuel

Misconceptions about energy and energy related concepts can lead to challenges in understanding other fundamental concepts, particularly in science, and in turn deter students from pursuing STEM careers.

Research Objective and Rationale

Knowledge about energy (states, forms, sources, and applications) is often presented as a part of STEM curriculum. However, given how essential it is to human existence, it should be considered general knowledge and taught to all high school students. In the this study, the research focus is to deliver accurate concepts on **energy and energy conservation**, and show the value and benefits of **renewable energy** through the development of **energy curriculum** for high school students, which will include **instructional materials and manipulatives for hands-on engagement**.

The research objectives are as follows:

1. Develop instructional material on energy and biogas
2. Evaluate the effectiveness of the instructional materials in terms of student learning
3. Design and test an anaerobic digester to serve as an instructional manipulative for teaching about biogas
    a. Develop and execute a 2^3 factorial designed experiment to identify which combinations of selected factors lead to maximum production of biogas in the anaerobic digester

Accomplishing the research objectives required the combination of techniques from three major disciplinary areas, i.e., engineering education, environmental engineering, and industrial engineering as seen in Figure 1. Engineering education, which is the study of how engineers learn to be practitioner, served as a platform to the **development of the curriculum** using an engineering design pedagogical framework and other prominent learning theories and practices. It also guided the **evaluation of the curriculum's effectiveness in helping students learn**. Environmental engineering, which integrates science and engineering principles to improve the natural environment, served as a platform for the **design and development of a classroom sized anaerobic digester which served as an instructional manipulative** for helping students understand the production and applications of biogas. Industrial engineering, which deals with the optimization of complex systems, served as a platform for the **designed experiment, conducted to identify which combinations of the selected factors lead to the maximum production of biogas.**

As indicated, each of the identified disciplines brings a different lens of analysis to bear on this research, which may not always be compatible with each other. As a result, this research will be presented in two separate articles to adequately address the dual dimension of this work. The first article focuses on the design, implementation, and evaluation of the curriculum design. The second article focuses on the development of the instructional manipulative: the anaerobic digester; and the 2^3 factorial designed experiment used to identify the combination of selected factors that leads to maximum biogas production.

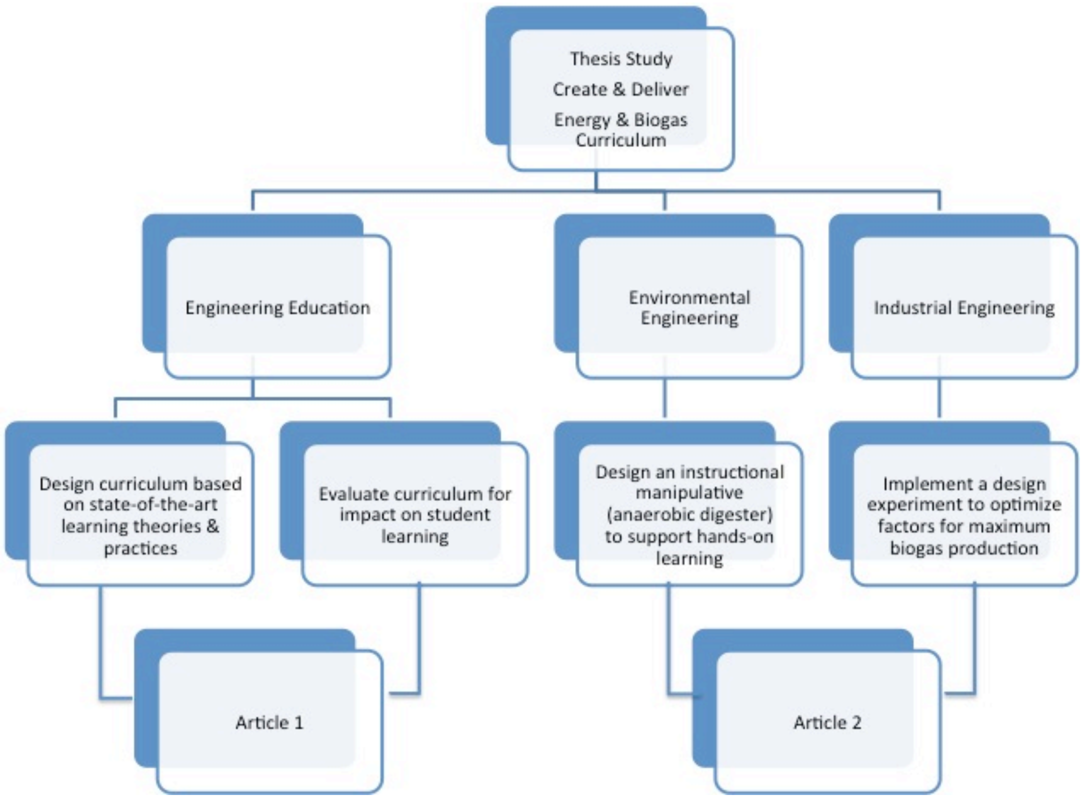


Figure 1. Multidisciplinary nature of the proposed work

Articles

This thesis comprises the following two articles:

1. McCall, S. Teaching Energy Concepts using Chain Reaction Machines. Not Submitted[1]
2. McCall, S. 2^3 Designed Experiment to Improve Biogas Production in an Instructional Manipulative. Not Submitted

The following references refer to additional work generated from this thesis. Each has been accepted or presented in an academic forum:

1. McCall, S., Dalrymple, O., Taylor, R., & Jordan, S. (2014). Teaching Energy Concepts using Chain Reaction Machines. American Society of Engineering Education, 1–10.
2. McCall, S., Dalrymple, O., & Jordan, S. (2014). Curriculum Exchange: Teaching Energy Concepts using Chain Reaction Machines. *American Society of Engineering Education*, 1–2.
3. McCall, S., & Dalrymple, O. (2014, February 11). Optimizing Plug-Flow Anaerobic Digesters to K-12 Basic Process of Anaerobic Digestion. Presented at the 2014 Gatekeeper Regulatory Roundup- Helping Communities through Climate and Environmental Challenges, Scottsdale, Arizona.

[1] This article is a revision of the following published article: McCall, S., Dalrymple, O., Taylor, R., & Jordan, S. (2014). Teaching Energy Concepts using Chain Reaction Machines. American Society of Engineering Education, 1‑10.

4. McCall, S., & Dalrymple, O. (2014, February 11). Optimizing Plug-Flow Anaerobic Digesters to K-12 Basic Process of Anaerobic Digestion. Presented at the Biodesign Institute at Arizona State University, Tempe, Arizona.
5. McCall, S., & Dalrymple, O. (2014, April 1). Experimental Design to Improve Biogas Production from Cow Manure. Presented at the Third Annual Student Conference on Renewable Energy Science, Technology and Policy, Arizona.

CHAPTER 2

ARTICLE 1- TEACHING ENERGY CONCEPTS USING CHAIN REACTION MACHINES

Study Overview

Background literature.

The Next Generation Science Standards (NGSS), which are based on the Framework for K-12 Science Education, establish principles for overcoming negative trends in K-12 educational outcomes in the United States [8]. The NGSS put forth "a new vision for American education," focusing on student performance rather than on specific curriculum guidelines. The goal of instruction is to provide students with a context for the concepts being taught in order to enhance their understanding of how scientific knowledge relates to the world in which they live [9]. The Framework for K-12 Science Education for middle and high school students (grades 6-12) addresses topics such as [10]:

- Definitions of energy
- Conservation of energy and energy transfer
- Energy and matter
- Natural resources
- The influence of science, engineering, and technology on society and the natural world
- Defining and delimiting engineering problems and developing possible solutions

The NGSS sets student performance outcomes based on these topics. One of the five energy performance outcomes for high school students states that the students should be able to “design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy” [10].

Study objectives.

1. Design and implement energy and biogas content modules to fit into the STEAM Machines™ Curriculum
2. Evaluate the effectiveness of the instructional materials and manipulatives in terms of student learning

Implementation Environment

STEAM Machines™.

The STEAM Machines™ summer camp curriculum introduces students to the previously mentioned science and engineering topics through the construction of Rube Goldberg-style chain reaction machines. After being given a simple task to complete (e.g. zipping a zipper or hammering a nail), students learn and apply the engineering design process as they plan and build their chain reaction machines. The construction of a chain reaction machine is a powerful vehicle for introducing students to technical information because of the ability of these machines to capture students’ interest and to spark their imagination. A 2007 survey of 319,223 students in the United States, Canada, Australia, and Mexico found that “a large portion of K-12 students who have experienced hands-on, tangible activities and group-oriented learning methods in STEM subjects found them to be the most interesting” [11]. The STEAM Machines™ summer camp programs utilize such group-oriented and hands-on activities to teach real-world engineering skills, provide experience with systems thinking and multi-team collaboration, integrate arts with science, technology, engineering, and math (STEM), and create a pathway for students to better understand careers in engineering and other STEM fields.

The STEAM Machines™ program spans 5-days, with approximately 35 contact hours. Students spend a significant amount of time learning the engineering design process and applying the process to the design and construction of chain reaction machines. Engineering design activities are powerful strategies for the integration of science, mathematics, and technology, and for engaging a broad population of students [11]. Dispersed throughout the week are hour-long modules on various science, technology, math and art concepts. Including art concepts in STEM increases interest in science and includes students who are more artistically inclined [12]. These modules are presented just-in-time for the students to apply them to the design and development of their machines. Many STEM programs use the "just in time" approach by using remote access technology as a tool to connect with mentors and students at other schools [13]. Table 1 shows a breakdown of a typical camp schedule.

A chain reaction machine consists of a number of action–reaction steps in sequence. According to the official Rube Goldberg Machine Contest rulebook, a step is defined as, "the transfer of energy from one action to another action." [14]. Understanding energy and how it facilitates work, is essential to the task of designing and building chain reaction machines. It is vital that students establish a strong foundational understanding of energy concepts and the roles that energy plays in engineered devices.

Given the urgency of energy issues in our world today, it is essential for energy to take a prominent role in the science curriculum [15].

Summer 2013 experience.

For the Summer 2013 implementation of the STEAM Machines™ summer camp programs, new content modules on energy and biogas were integrated into the curriculum and introduced at three high school sites, i.e.; two in Arizona and one in Trinidad and Tobago. Energy and biogas modules were scheduled on the first day of camp. They were both presented in the later part of the day, following a mini exercise in creating a chain reaction machine. This mini exercise provided a shared experience that could be referred to and used to introduce and explain energy and biogas concepts.

Time	Monday, July 22	Tuesday, July 23	Wednesday, July 24	Thursday, July 25	Friday July 26
9:00 AM	SDP 01 (1 hr) Introduction to Chain-Reaction STEAM Machines™	ASM 15_1, ASM 06_1 (15 min) ▪ STEAM Interest Pretest ▪ Simple Machines Pretest	ASM 06_2, ASM 08_1 (15 min) ▪ Simple Machines Postest ▪ Electricity Pretest	ASM 15_2 (15 min) ▪ STEAM Interest Posttest	ASM 05_2 (15 min) ▪ Career Plans Posttest
9:15 AM		CNT 09 (1 hr) Simple Machines	CNT 05 (1 hr) Electrical Energy	SDP 10 (30 min) Plan and Create	SDP 16 (1 hr + 15 min) Systems Integration, Test and Improve
9:30 AM	▪ ASM 01 Tell Us ▪ ASM 02_1 Design Scenario Pretest				
9:45 AM				CNT 08 (45 min) Testing for Reliability	
10:00 AM	SDP 02 (30 min) Human STEAM Machine™				
10:15 AM		Break	Break		
10:30 AM	Break	CNT 02 (30 min) Machine Quality and Storyboarding	SDP 04 (30 min) Ask, Imagine, and Plan	Break	Break
10:45 AM	CNT 01 (45 min) Introduction to the Engineering Design Process			CNT 10 (30 min) Anaerobic Digester	SDP 16 (1 hr) Systems Integration, Test and Improve
11:00 AM		SDP 04 (1 hr) Ask, Imagine, and Plan	SDP 10 (1 hr) Plan and Create		
11:15 AM				SDP 10 (45 min) Test, and Improve	

Table 1: In the color-coded schedule, most of the sessions, shown in brown, were geared towards learning and applying the engineering design process. The sessions in yellow are the science, technology, arts and math content modules. These sessions are presented just-in-time for students to apply them to the design and development of the machine.

Like all of the instructional activities in the STEAM Machine™ curriculum, the delivery of the energy and biogas content modules incorporated three key pedagogical strategies [16]: 1) building off of prior knowledge; 2) hands-on engagement; and 3) collaborative learning. The implementations of these strategies will become more evident through the discussion that follows on the design and implementation of both modules.

High-school participants.

A total of 65 students from: Red Mountain High School (RM) in Mesa, AZ, Highland High School (HHS) in Gilbert, AZ and Bishop Anstey High School East & Trinity College East (BATCE) in Trincity, Trinidad & Tobago, ranging from ages 13 to 18, participated in the experience. However, only 39 students were evaluated on the STEAM Machines ™ curriculum, and newley added energy, and biogas module as shown in Table 2. Complete assessment data i.e., pre- and post-tests were not collected from the remaining 26 students.

Table 2. Demographic break-down of group evaluated

School	Female	Male	Total
RM	4	7	11
HHS	5	14	19
BATCE	5	4	9
Total	14	25	39

Methods

Outcome-based curriculum design method.

The curriculum was designed using the outcome-based education (OBE) curriculum design method. OBE is an approach where the product defines the process. The outcomes that specify what students should be able to know, understand, or do upon completion of the modules are defined first, and drive decisions about the instructional approach, i.e., the learning activities that help students achieve the outcomes, and the assessment criteria i.e., the metrics usd to assess the extent to which students meet outcomes.

Energy curriculum learning objectives.

The energy module was designed to help students learn about the different states, forms and sources of energy. On completion of the energy module students were expected to:

- Identify the different states and forms of energy
- Describe the Law of Conservation of Energy
- Describe the difference between renewable and non-renewable sources of energy
- Describe things that can be done on a national and individual level to use energy sustainably
- Design chain reaction machines with constraints related to forms of energy

Biogas curriculum learning objectives.

The biogas module was designed and developed to teach students about anaerobic digestion, anaerobic digestion process, and the by-products produced. Upon completion of the module, students were expected to:

- Describe the process of anaerobic digestion
- Describe how biogas is created and its applications
- Create biogas and use the resulting energy to power a step in a chain reaction machine

Instructional aproach.

Three learning theories were chosen as an instructional approach: building off of prior knowledge, collaborative learning, and use of instructional manipulatives for hands-on engagement as shown in Figure 2.

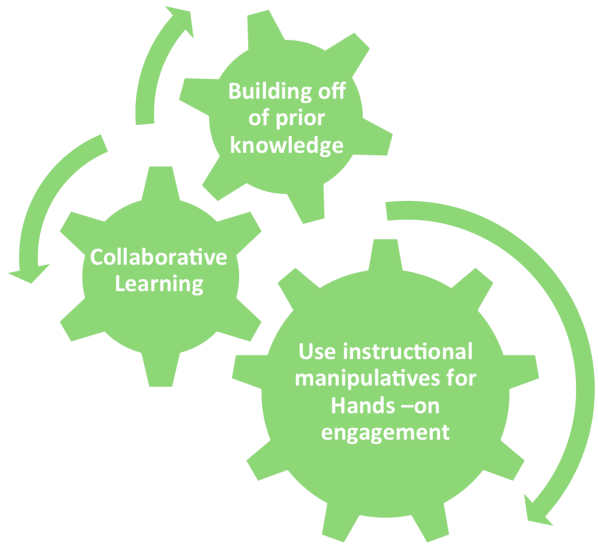


Figure 2. Applied learning theories

Assessing prior knowledge.

Throughout the presentation before a new concept was discussed, the presenter gathered information from the students on their prior knowledge and understanding. This insight was then tied into the discussion and helped facilitate the presentation of new material. To build off prior knowledge the following steps were followed:

1. Pose initial question
2. Gather responses
3. Acknowledge accurate responses and correct any misconceptions
4. Build on students' prior experiences

An example of building off prior knowledge can be seen in Figure 3.

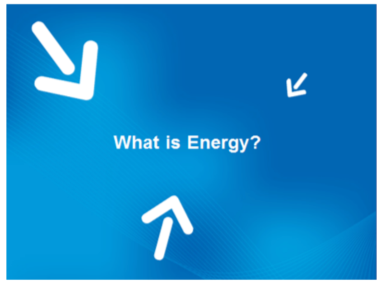


Figure 3. Students' prior knowledge was assessed before discussing content modules

Collaborative learning.

To continue to engage the students and create a collaborative learning atomosphere, challenges were placed throughout the presentation to reinforce concepts that were previously covered. For example, in Figure 4 teams of students were given a stack of Post-It-Notes™ to label the forms of energy in their mini chain reaction machine. Each team then presented their completed challenge, followed by oral feedback from other students and the instructor.

Figure 4. Students label their constructed manipulative to show the transition to the different states and forms of energy

Hands-on engagement.

On example of hands-on learning occurred when teams of students engaged in a laboratory experiment to produce biogas using a class-room sized anaerobic digester. Students were responsible for transferring the knowledge gained from the presentation to an application by mixing manure with water to create a slurry. Figure 5 shows the instructional manipulative, i.e., the anaerobic digester, being set-up. Students followed the laboratory and safety procedures, which are included in Appendix A.

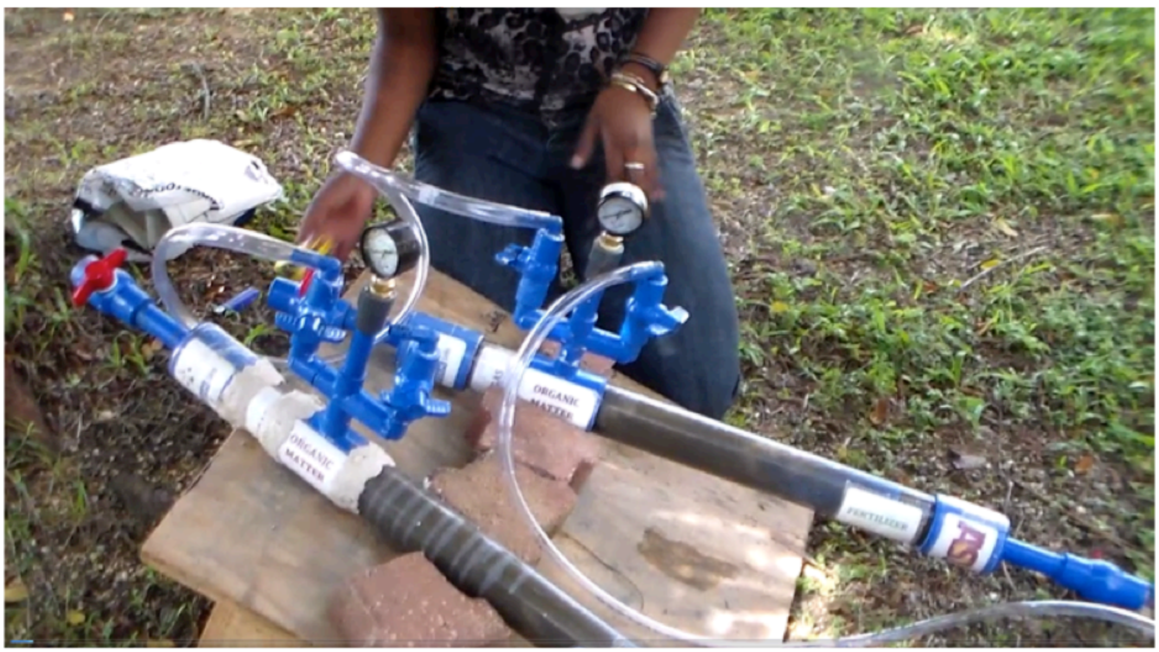
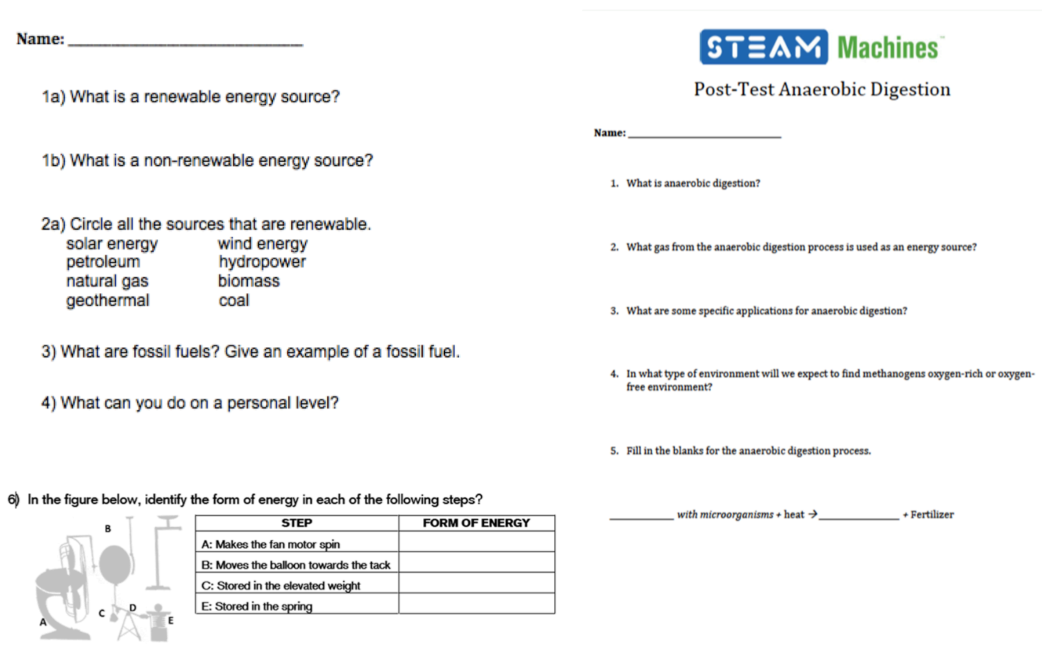


Figure 5. Instructional manipulative used as a hands-on teaching instrument

Evaluation: results from learning assessments

Learning from the energy and biogas content modules was assessed using a pre- and post-assessment. The energy module consisted of questions that tested students' recall and understanding of: different states and forms of energy, Law of Conservation of Energy, difference between renewable and non-renewable sources of energy, and things that can be done on a national and individual level to use energy sustainably. The biogas module consisted of questions that tested students' recall and understanding of: anaerobic digestion processes and description of how biogas is created and its applications.

The pre-test was administered prior to the presentation of the content modules. Two to three days after the delivery of content modules the post-tests was administered. The results from the two assessments (pre and post assessment) were then compared using a paired t-test. Figure 6. shows examples of questions from the pre/post assessment tools.


Name: ______________________

1a) What is a renewable energy source?

1b) What is a non-renewable energy source?

2a) Circle all the sources that are renewable.

solar energy	wind energy
petroleum	hydropower
natural gas	biomass
geothermal	coal

3) What are fossil fuels? Give an example of a fossil fuel.

4) What can you do on a personal level?

6) In the figure below, identify the form of energy in each of the following steps?

STEP	FORM OF ENERGY
A: Makes the fan motor spin	
B: Moves the balloon towards the tack	
C: Stored in the elevated weight	
E: Stored in the spring	

STEAM Machines

Post-Test Anaerobic Digestion

Name: ______________

1. What is anaerobic digestion?

2. What gas from the anaerobic digestion process is used as an energy source?

3. What are some specific applications for anaerobic digestion?

4. In what type of environment will we expect to find methanogens oxygen-rich or oxygen-free environment?

5. Fill in the blanks for the anaerobic digestion process.

________ *with microorganisms* + heat → __________ + Fertilizer

Figure 6. Pre and post assessment tools

Results

Energy content module assessment results

Of the 39 participating students, 30 completed both pre/post assessments for the energy content module. The pre/post assessments were both scored out of 10 points.

Based on the paired t-test analysis, students' knowledge of energy concepts after module (7.47± 1.5) was statistically higher than their knowledge of energy concepts before module (5.83 ± 2.18), t (29)= -4.001, $p<0.05$.

Only eight participating students in Trinidad and Tobago completed both assessments for the biogas content module. Pre/post assessments were both scored out of 100%. Based on paired t-test analysis, students' knowledge of biogas production after the module (0.84 ±0.16) was statistically higher than their knowledge of biogas before the module (0.14 ± 0.15) t (7)= -9.975, $p<0.05$.

Conclusion

Our results indicate that through our energy and biogas content modules the students were able to better comprehend energy concepts and biogas as an energy source along with the engineering design process. The pre-assessment average score was 5.83 out of 10 points possible. After the deliberation of the energy content module the student post-assessments scores increased to 7.47 out of 10 points. The same increase in knowledge was seen in the biogas production module (pre-assessment 0.14 out of 100% to post-assessment 0.84 out of 100%). The information gained by the students, especially for biogas production, was significant and showed that the content modules increased students' knowledge.

To advance the study and gain more insight to students learning, an assessment administered one-year after the program should be done. This one-year later assessment would have the same assessment questions as the pre- and post-test administered previously. The results from this one-year later assessment should show whether or not the students were able to retain the information and commit to long-term memory.

CHAPTER 3

ARTICLE 2- DESIGNED EXPERIMENT TO IMPROVE BIOGAS PRODUCTION IN AN INSTRUCTIONAL MANIPULATIVE

Study Overview

Background literature.

From reports of early human civilization, people have burned logs, straw, wood, and animal waste—to create energy [17]. This form of energy is known as biogas and is one of the most used and oldest sources of energy. Biogas is the by-product of decomposing organic waste under anaerobic conditions and heat. The chemical formula is as follows: $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$. The by-product, decomposed organic waste, is high in nitrogen and phosphorus and can be used as fertilizer [18].

There are suggestions that biogas was used for heating bath water in Assyria as early as the 10th century B.C. and that anaerobic digestion of solid waste may well been applied in ancient China [19]. As modern technology developed and the cost of energy became more affordable and easily accessible, many people in developed countries deterred from biogas and used fossil fuels as a primary energy source. As a result, greenhouse gas emission increased. Contrary to developed countries, most of the biomass-based energy is consumed in developing countries for cooking, heating, and lighting; accounting for approximately 10% of the world's total primary energy supply [20]. As time has progressed, research and studies have been conducted to show the adverse effect of not using bioenergy as a source. Through research, scientist were able to discover that cow burps have twice as much methane as conventional reared cattle—and methane is 20 times more powerful a greenhouse gas than carbon dioxide [21]. By not using the burp, let alone the manure from the cow, methane is released into the atmosphere instead of being used and combusted and broken down into less harmful gases. Recently, modern bioenergy production has grown steadily to achieve significant greenhouse gas reduction along with other alternative energy solutions [20]. With recent increase in bioenergy for heat and power supply, it is important to educate high school students about the applications of biogas production in order to further reduce green house gas emissions and encourage a more sustainable lifestyle.

Study Objectives

1. Design an anaerobic digester to serve as an instructional manipulative in a high school classroom setting
2. Identify factors which can be easily manipulated in a high school environment and impact the production of biogas
3. Identify the combinations of factors that will yield the highest amount of biogas

Methods

Design requirements.

Constructing the instructional manipulative, i.e., a plug-flow anaerobic digester presents many requriements for the design given the setting, student demographics, application, and saftety standards in schools. In order to ensure that the digester serves its desired educational purposes the instructional manipulative should be equally accessible to schools or programs that have large budgets or limited resources. Therefore, it was designed with low-cost materials. In addition, it is likely the lesson will be conducted in a room that may not have laboratory equipment. Therefore, the instructional manipulative was designed to be used in or outside of a laboratory environment. To adhere to students who are visual learners, it is important for the anaerobic digester to serve as an instructional manipulative which visually shows the process of anaerobic digestion and renders biogas. Therefore, transparent components were used to show the processes occuring inside the digester. Figure 8 shows the requirments for the instructional manipulative.

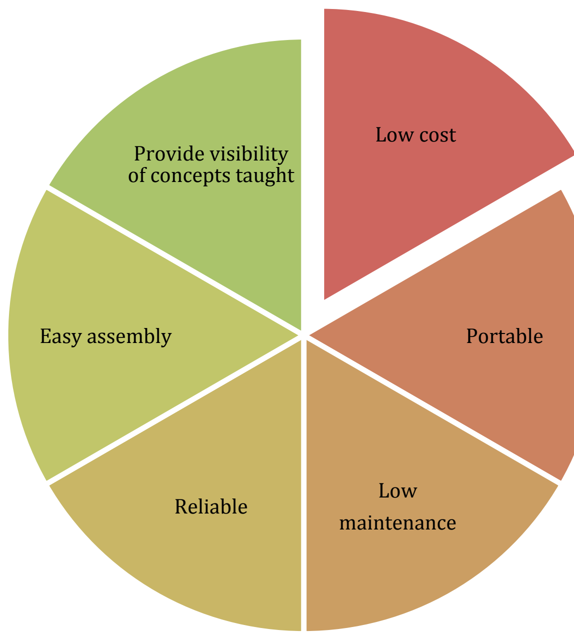


Figure 8. Design requirements for instructional manipulative (anaerobic digester)

Design and factors of anaerobic digester.

To facilitate learning and understanding of the applications of biogas an instructional manipulative, i.e., a plug-flow anaerobic digester, was created using polyvinyl chloride (PVC) pipe, PVC fittings, brass ball valves, and pressure gauges.

Plug-flow anaerobic digesters are effective in helping high school students learn about renewable energy sources because it is low maintenance and it can be implemented in any classroom setting [22].

1st design.

The 1st design of the plug-flow anaerobic digester had a diameter of 0.051m and 0.61m in length and positioned on a 45° angled rack. The digester had an inlet and outlet located six inches from the top of the digester and at the bottom of the digester respectively. The digester was able to hold 1.0L of slurry and had a six-inch gas chamber, latex balloon attached to flexible tubing, located in the middle of the digester for collecting biogas. PVC piping and connectors were held together by PVC cement glue. This design was used as an instructional manipulative in Summer 2013 for students in Arizona. The 1st design drawing is seen in figure 9.

Flaws in 1st design.

In order to have the gas collected in the middle of the digester, a hole had to be drilled. A PVC connector was attached with plastic epoxy adhesive to attach the PVC connector and the 2” pipe, but when the digester was moved it weakened the bond allowing gas to escape. Another flaw in the design was using a latex balloon fastened with a metal clamp onto the flexible tubing to collect the biogas from the digester. The metal clamp did not give an airtight seal and the balloon was destroyed in the sun over prolonged periods of time. Since there were flaws in the design students were unable to experience the production and application of biogas [22].

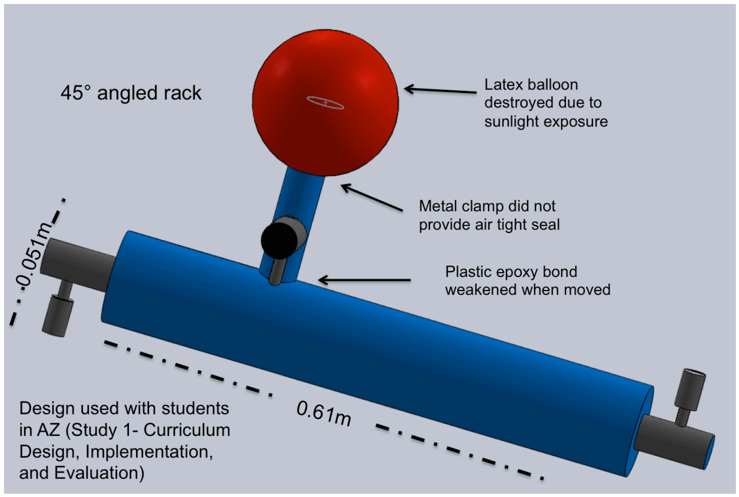


Figure 9. 1st design of instructional manipulative, plug-flow anaerobic digester (Drawn using SolidWorks®)

2nd design.

The 2nd design of the plug-flow anaerobic digester had a diameter of 0.051m and 0.61m in length and was positioned on a vertical rack allowing sludge to face down and created a vacuum. The digester had an inlet and outlet located six inches from the top of the digester and at the bottom of the digester respectively. The digester was able to hold 1.0L of slurry and has a six-inch gas chamber for collecting biogas. In the middle of the digester was a threaded 2" coupling which allows the two ball valves with flex pipe elbows and one pressure gauge to be screwed in with a 1/2" nipple. Both flex pipe elbow ball valves are shut-off and are used for collecting biogas into the balloon. PVC piping and connectors were held together by PVC cement glue. Teflon tape was added to all threaded PVC fixtures and brass ball valves. The 2nd design drawing is seen in figure 10.

Flaws in 2nd design.

Since the flex pipe elbow, ball valve, and pressure gauge was located in the middle of the digester it was prone to clogging and blocked the collection of biogas.

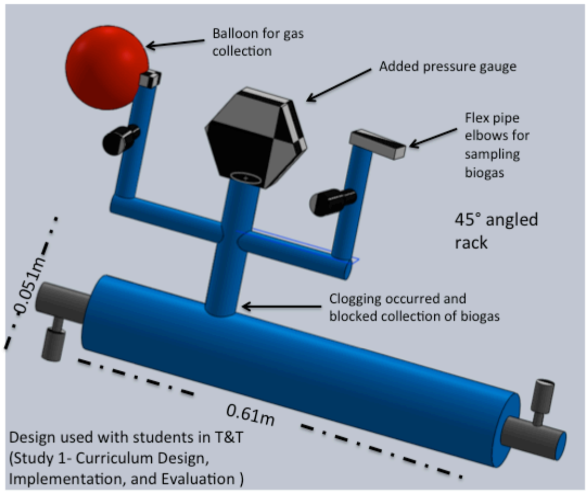


Figure 10: 2nd design of instructional manipulative, plug-flow anaerobic digester (Drawn using SolidWorks®)

Final design.

The final design of the plug-flow anaerobic digester had a diameter of 0.051m and 0.61m in length, and was positioned on a vertical rack allowing sludge to face down and created a vacuum. The digester had an outlet located six inches from the bottom of the digester. The inlet was a ball valve located in the middle of the digester screwed into a 2" PVC coupling with a ½" nipple. The digester was able to hold 1.0L of slurry and had a six-inch gas chamber for collecting biogas. At the top of the digester is a 2" threaded coupling which allows the two ball valves with brass barb adapter and one pressure gauge screwed in with a ½" nipple. Both ball valves are shut-off with an aluminum gasbag, used for collecting biogas, attached to one of the brass barb adapters. PVC piping and connectors were held together by PVC cement glue and Teflon tape was added to all threaded PVC fixtures and brass ball valves. The final design drawing and digester is seen in figure 11 and 12.

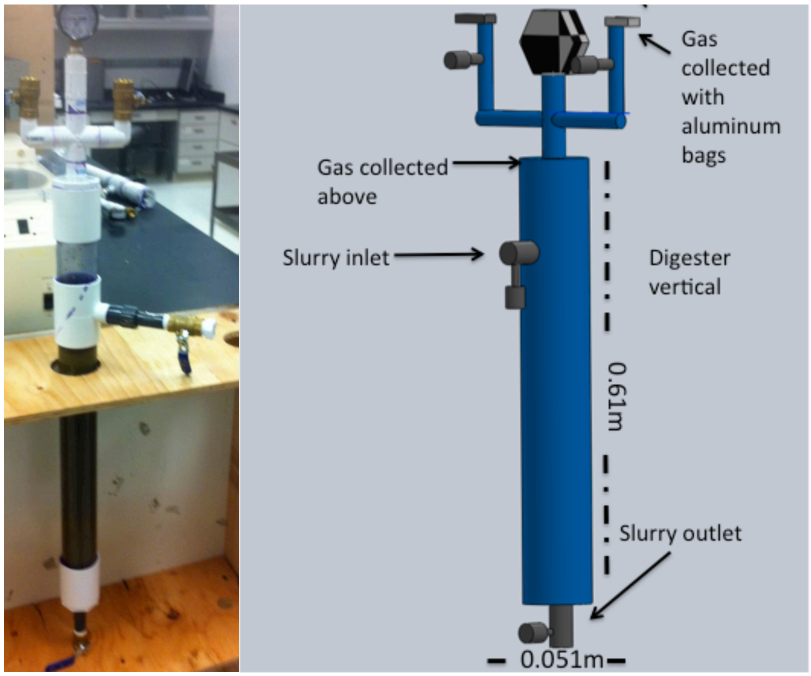


Figure 11&12: Final design of instructional manipulative, plug-flow anaerobic digester (Drawn using SolidWorks®)

Testing of final design.

The main purpose of adding the pressure gauge was to test the seal and verify whether or not there were any leaks. 1.0L of water was added to the digesters and pressurized at 10psi and monitored for 72-hours to observe any possible leaks. After a 72-hour period the digesters remained pressurized at 10psi indicating that there are no leaks.

2^3 Designed Experiment

Organic waste and factors for anaerobic digester.

The organic waste going into the digester to produce biogas needs to be easily accessible, can be used in a non-STEM classroom, and easily manipulated. The following materials are used as organic waste: manure, used cooking oil, and inoculum. The manure was collected from Superstition Farm located in Mesa, Arizona. The farm has approximately 1500 cows that are feed hay, cottonseeds, walnut shells, silage, and sometimes corn.

Objective.

The goal of the experiment is to find which combinations of factors [temperature, inoculum, and used cooking oil] will yield the highest amount of biogas.

Hyptothesis.

H_o: The mean biogas for all digester is statistically equal under the 8 different conditions

H_a: The digester with the **factors 20mL used cooking oil and 40°C** will produce statistically **higher biogas** than other factors

Factors.

To ensure that students gain the full experience of producing biogas, it is important to discover factors that lead to the maximum amount of biogas production. The following factors were chosen based on previous studies, typical climate conditions, and factors that can be easily manipulated: used cooking oil, temperature, and co-digestion of inoculum. Refer to Table 3. Lipids-rich waste such as used cooking oil, is a favorable substrate for anaerobic digestion and co-digestion due to the higher methane yield obtained when compared to proteins or carbohydrates [23]. 2.5% of the digester volume of used cooking oil added into digester and had the greatest methane production and no adverse effects were observed from co-digestion [18]. Use of used cooking oil in digesters protect water resources and is a profitable way of disposing oil [24]. Optimum temperature of mesophilic digester for biogas production is 35°C. In the mesophilic range, the activity and growth rate of bacteria decrease by 50% for each 10°C drop [25]. The camps have been conducted in the summer in Arizona and Trinidad & Tobago. The average summer monthly temperature in the summer of Trinidad & Tobago is approximately 25°C. The average summer monthly temperature in Arizona is 40°C. Co-digested inoculum increased the amount of gas produced since there is an active microbial community [26]. To produce inoculum manure was placed into the digester for 2-weeks prior to running experiments.

Table 3. Factors that yield greatest amount of biogas production assessed at high and low settings

Factors	High	Low
Used Cooking Oil: Carbon-rich food waste lipids increase methane production [23].	50mL	20mL
Temperature: Values between 32.2°C-38°C yield high amounts of biogas [25]Temp. levels chosen based on typical climate conditions.	40°C	25°C
Inoculum: Previously digested manure. increase the production of biogas [26].	200 ml	0 ml

2^3 Factorial Design.

The study was conducted in Dr. Hinsby Cadillo-Quiroz laboratory at Arizona State University. Twelve plug-flow anaerobic digesters made of PVC piping and fixtures were used in a 2^3 factorial design with three replications assessing: co-digestion (2% or 5% used cooking oil), temperature (25°C or 40°C), and addition of inoculum (0mL or 200mL). Refer to table 4 and figure 13 to see the digester set-up. Biogas production was captured at two intervals over a 30-day period. Table 5 shows the designed experiment for the digesters.

Table 4. Digesters factors and groups

Dig.	Factors (T|I|O)	Grp.
1	-|-|-	1
2	+|-|-	1
3	-|+|-	2
4	+|+|-	2
5	-|-|+	1
6	+|-|+	1
7	-|+|+	2
8	+|+|+	2

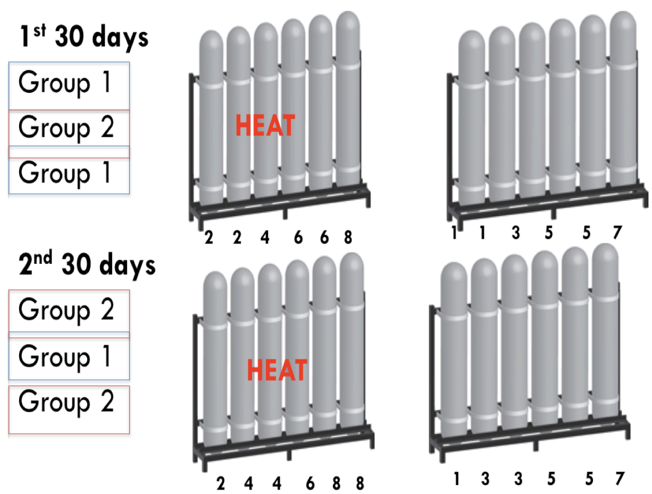


Figure 13. Designed experiment set-up

Table 5. 2^3 Designed experiment

Dig.	Temp.	Inoc.	Oil
1	25°C	0mL	20mL
2	40°C	0mL	20mL
3	25°C	200mL	20mL
4	40°C	200mL	20mL
5	25°C	0mL	50mL
6	40°C	0mL	50mL
7	25°C	200mL	50mL
8	40°C	200mL	50mL

Data collection procedures.

In order to make slurry, 300g of wet manure and 1.0L of water were combined. Next, 1.0L of slurry was added into each digester. Those digesters requiring inoculum were administered inoculum on Day 1 only. After a 10-day interval digesters were relieved half (500mL of the slurry) and fed half of the prescribe mixtures (500mL of slurry). Half of the mixture in each digester remained to ensure microbial community activity continued to thrive.

Influent and effluent samples were collected at 10-day intervals from February 3, 2014 to March 3, 2014 and March 12 to April 11, 2014. The samples' pH and temperature were analyzed using a hand-held probe. See Appendix B for pH and temperature readings. Biogas production was measured by collecting the biogas in Sigma-Aldrich 1.0L foil sampling bags and then measured by submerging the bags in water and inverting water column over gasbag. This was done once on the 10th and 30th day. Biogas composition was determined twice throughout both experiments, once on the

10^{th} and 30^{th} day with a gas chromatography. Figure 14 is a pictorial diagram of the experimental procedures.

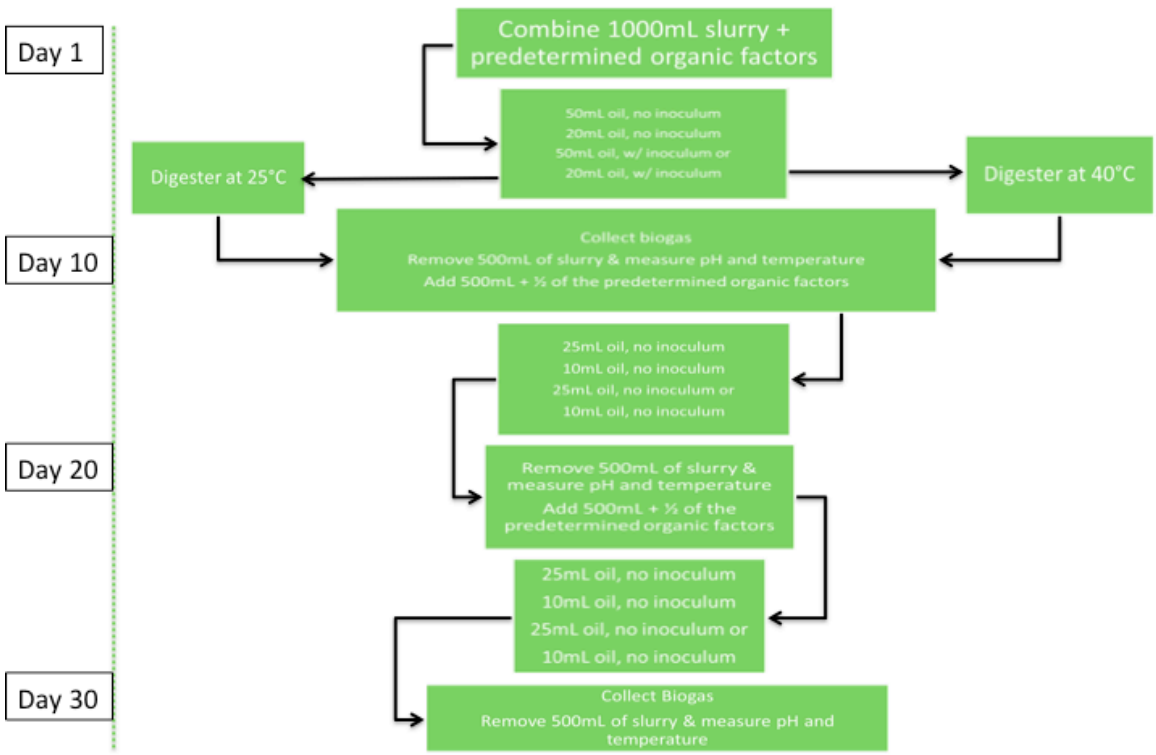


Figure 14. Experimental procedures

Results

The experimental design aided in discovering the combination of factors that will have the most significant impact on the production of biogas. The experimental design statistical analysis was evaluated using Minitab®. At $\alpha = 0.05$ temperature at 40°C significantly increased biogas production and should be used over 25°C when using anaerobic digesters. Refer to figure 15. Other factors that may potentially increase biogas production are 50mL of used cooing oil and 200 mL of inoculum. Refer to table 6 and figure 16, 17, and 18.

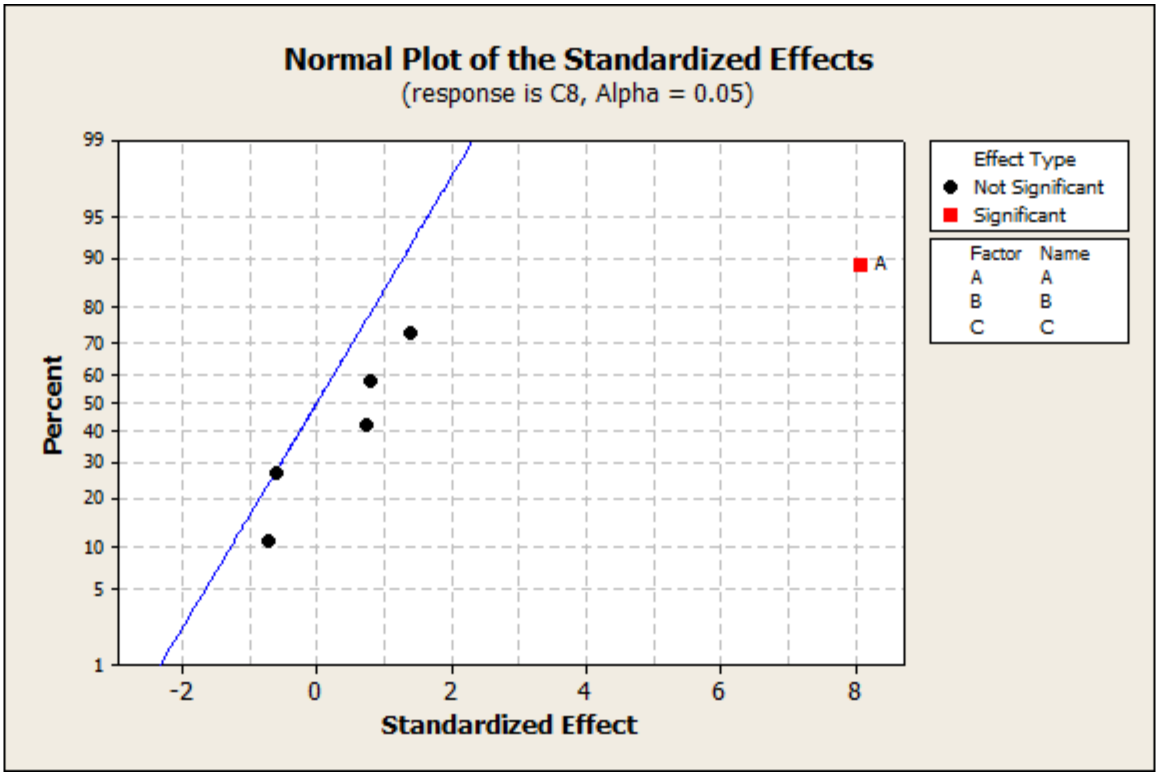


Figure 15. Normal plot of standard effect showing temperature is a significant at $\alpha = 0.05$

Table 6. Factors showing mean effects and p-value outcomes

Factors		Effect	P-Value
A	Temperature	336.50	0.000
B	Inoculum	-24.67	0.561
C	Used Cooking Oil	30.83	0.469
A*B	Temperature*Inoculum	-29.33	0.490
A*C	Temperature*Used Cooking Oil	33.17	0.436
B*C	Inoculum *Used Cooking Oil	58.00	0.181

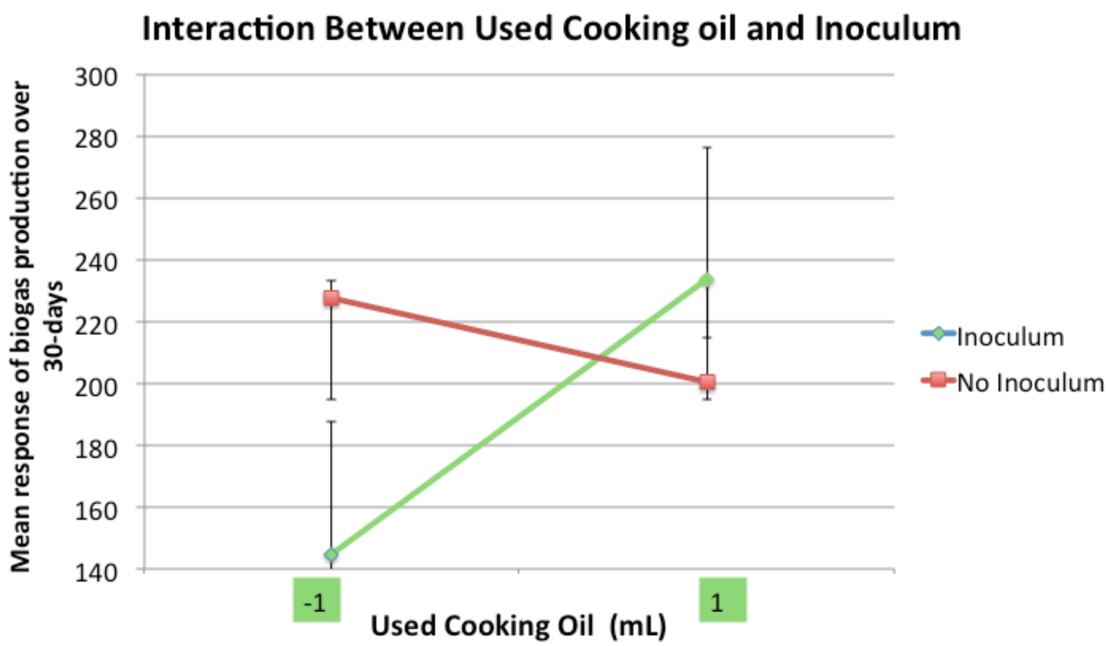


Figure 16. As used cooking oil increased from 20mL to 50mL the biogas production increased when inoculum is present. When inoculum is not present biogas production decreased as used cooking oil increases.

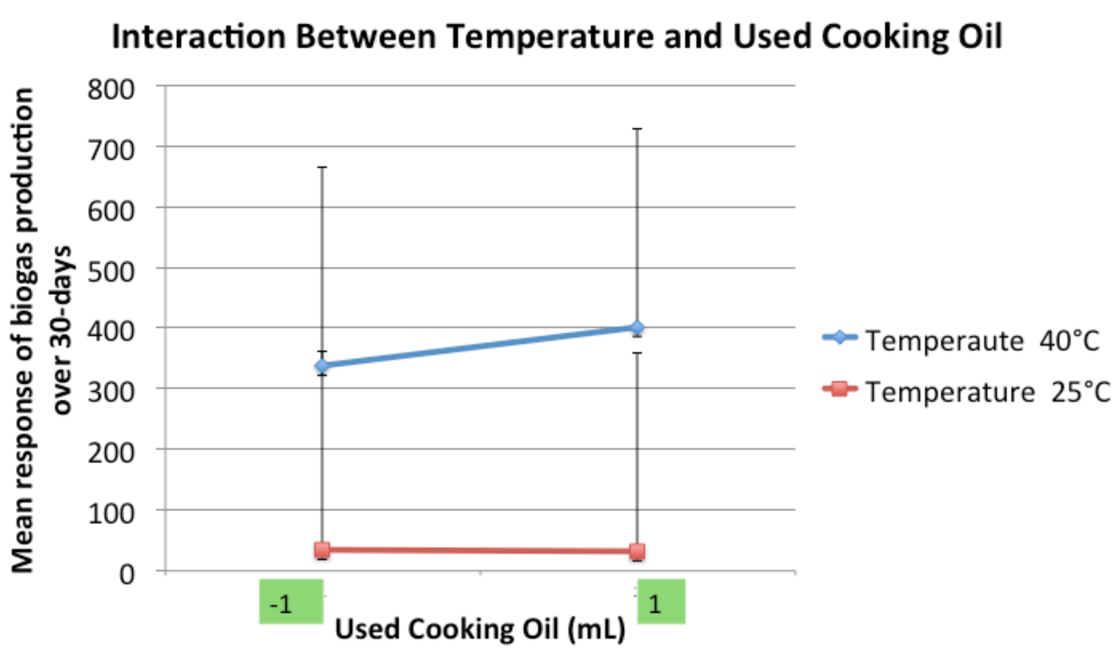


Figure 17. As used cooking oil increased from 20mL to 50mL the biogas production increased at 40°C. When temperature is 25°C biogas production decreased slightly as used cooking oil increases.

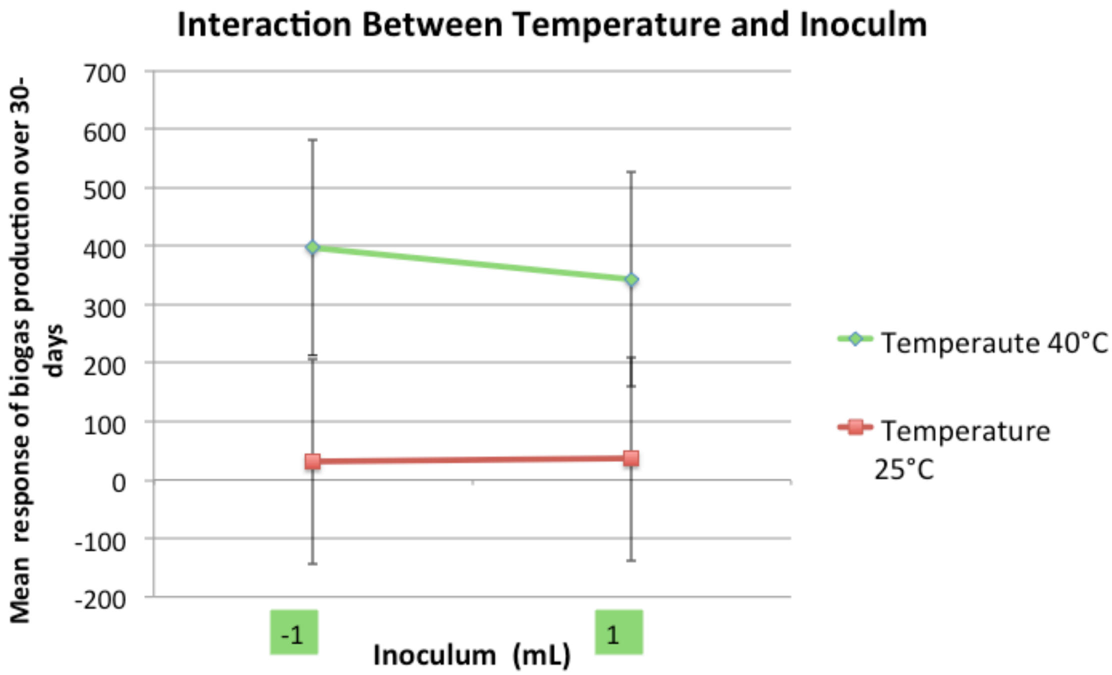


Figure 18. When inoculum is present biogas production decreases at 40°C. There is no change in biogas production when the temperature is at 25°C. and inoculum present and not present.

Average biogas production over 30-days.

Over the 30-day run time, digester 8 produced the most biogas, while digester 5 produced the least amount of biogas. Digester 8 factors are: temperature at 40°C, 200mL of inoculum, and 50mL of used cooking oil. Digester 5 factors are: temperature at 25°C, 0mL of inoculum, and 50mL of used cooking oil. Refer to table 7. The null hypothesis, the mean biogas for all digester is statistically equal under the 8 different conditions, is rejected. The mean biogas for all digester is statistically different under the 8 different conditions.

Table 7. Results of average biogas production from digesters

Dig.	Factors (T|I|O)	Avg. Biogas (mL)
1	-|-|-	38.3
2	+|-|-	416.67
3	-|+|-	30.67
4	+|+|-	259
5	-|-|+	23.67
6	+|-|+	377
7	-|+|+	40.67
8	+|+|+	426.67

Conclusion

Modification of the instructional manipulative improved the flaws in the 1st and 2nd design and led to the final design. Modifying and adding features improved design efficiency by detecting leaks, alleviating clogging, and providing pliable biogas storage. The final design aided in discovering factors that will lead to maximum production of biogas. The factor, temperature at 40°C, is shown to produce high yields of biogas rather than temperature at 25°C. Other factors that may potentially increase biogas production are the combination of 50mL of used cooking oil and 200mL of inoculum.

Previous literature indicates that inoculum by itself should have increased biogas production, however this was not seen. It was later discovered after the experiments that the inoculum was exposed to oxygen, possibly annihilating the microbial community activity, preventing biogas production. Given this information, future research can now be conducted to establish more specific range needed to identify factors that maximize the biogas production.

CHAPTER 4

GENERAL DISCUSSION

The created energy and biogas content module addresses energy misconceptions, encourages students to pursue careers related to energy conservation, and influences students' capabilities and desires to alleviate current energy issues on a global and individual scale.

In Article 1, the students were able to better comprehend not only the energy concepts, but also the engineering processes in the energy and anaerobic digestion modules. The research shows that students now comprehend energy concepts and are familiar with anaerobic digestion. Conducting energy projects is an effective way to engage students in the subject matter while applying this knowledge to solve problems that the students will ultimately inherit [15].

In Article 2, a modified instructional manipulative was designed and created to improve some of the flaws in the 1^{st} and 2^{nd} design and identified factors that will lead to maximum production of biogas. The improved design is shown to be reliable by discovering the factor, temperature at 40°C that will produce high yields of biogas.

In accordance with the NGSS, the energy and biogas production modules exemplify a 21st century approach to scientific learning in America. Students are exposed to foundational scientific principles in an interactive environment. Emphasis is placed not only on retaining scientific knowledge but also on applying that knowledge to solve a problem and on understanding the roles that scientific principles play in the world outside of their classroom.

The anaerobic digester module could be incorporated into the renewable resources lesson of a science class in order to help students understand the practical application of this concept. To aid in teaching of anaerobic digestion and biogas production, the plug-flow anaerobic digester will be donated to local high school teachers to facilitate learning of energy and biogas content.

To further the research, training offered to teachers would be beneficial to ensure that accurate information is taught to the students and understood by students, increase teachers' confidence in teaching energy and biogas modules, and inform teachers on how to use and operate instructional manipulatives.

Hopefully, the introduction of the new energy and biogas content modules will influence students and teachers' capabilities and desire to alleviate current energy issues on a global and individual scale.

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APPENDIX A

ANAEROBIC DIGESTION LAB PROCEDURES

STEAM Machines

Anaerobic Digestion Set-Up Lab

Name: ______________________________

Team Name: ______________________________

1.) Review Safety Protocol and handle manure carefully

2.) In a large beaker, measure 0.725L of manure and 1.25L of water, Combined amount should not exceed 2.0L

   a. Be sure to record exact amount of manure and water added on data sheet

3.) Combine the mixture until the consistency resembles a milkshake

   a. Don't drink it!

4.) Make sure digester bottom (closet to gas valve) bulb valve and gas valve is off

5.) Place funnel on open ball valve closets to gas valve and pour mixture (There should be enough space away from gas valve for the gas to accumulate)

6.) Close ball valve and wipe excess manure off of digester with Clorox wipes

7.) Ensure that all valves are turned off

8.) Clean work station with disinfectant

Figure 19. Biogas module lab experiment

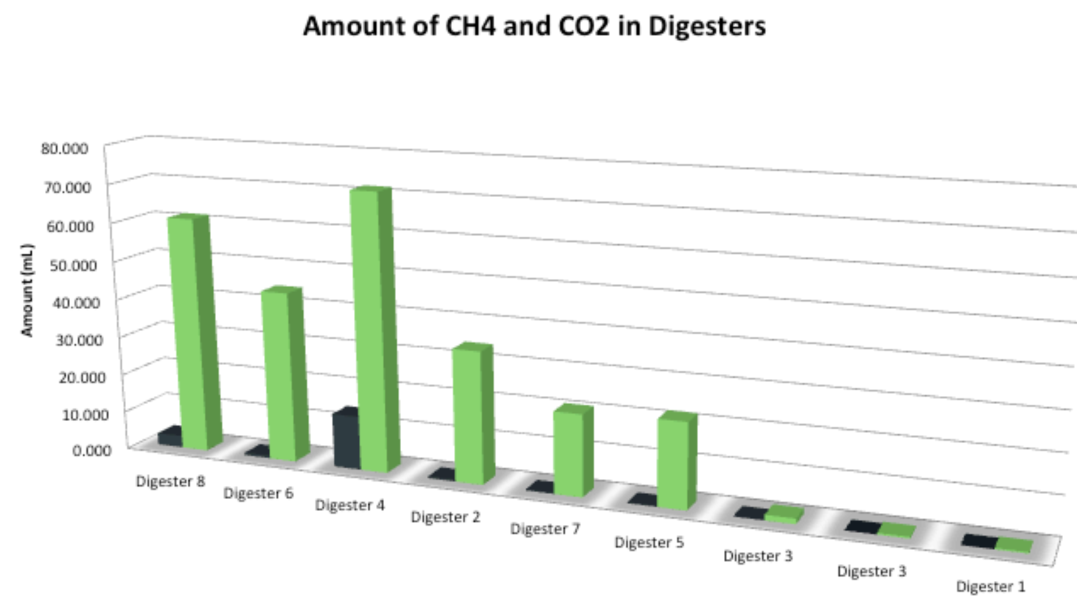
APPENDIX B

PH, TEMPERATURE, & BIOGAS READINGS

Table 8. Data analyzing digesters pH, temperature, biogas production over 30-days with 3 replications

			Day 1			Day 10			Day 20		Day 30			
Digester	Experiment	Trial	DAY1_pH	DAY1_Temp	DAYl_Biogas	DAY10_pH	DAY10_Temp	DAY_10Biogas	DAY20_pH	DAY20_Temp	DAY30_pH	DAY30_Temp	DAY30_Biogas	Total
1	1	1	6.26	23	0	5.57	25	10	5.03	26.4	4.92	24.5	32	42
1	1	2	6.34	23	0	5.2	26.6	10	4.04	28	5.16	24.5	10	20
1	2	3	6.23	23.2	0	5.37	24.2	34	5.37	24.2	4.82	24.2	19	53
3	1	1	6.31	23	0	5.19	26.4	24	4.91	27.4	4.87	24.2	10	34
3	2	2	6.19	21.9	0	5.16	24	20	5.16	24	4.85	24.1	3	23
3	2	3	6.35	23.2	0	5.22	23.8	5	5.22	23.8	4.82	24.2	30	35
5	1	1	6.5	23	0	5.14	25.8	25	5.03	25.6	5.08	24.2	10	35
5	1	2	6.38	23	0	5.14	25.8	30	5.02	25.8	5.03	24.7	2	32
5	2	3	6.47	23.4	0	5.07	23.1	3	5.07	23.9	4.83	23.9	1	4
7	1	1	6.4	23	0	4.88	26.4	38	4.84	25.4	4.96	25	1	39
7	2	2	6.08	23.4	0	5.14	23.5	3	5.14	23.5	4.75	23.9	30	33
7	2	3	6.53	23.4	0	5.11	23.7	1	5.11	23.7	4.58	23.9	49	50
2	1	1	6.47	23	0	5.3	38.4	18	5.04	36.9	4.94	38.6	500	518
2	1	2	6.45	23	0	5.24	29.4	120	5.01	45.8	4.93	38.6	187	307
2	2	3	6.55	24.1	0	5.7	46	165	5.7	46	5.06	42.3	260	425
4	1	1	6.59	23	0	5.27	30.8	59	5.29	48.1	5.04	35.1	110	169
4	2	2	6.39	23.6	0	6.39	23.6	70	5.09	34.4	5.1	40.8	170	240
4	2	3	6.45	23.3	0	6.45	23.3	99	5.35	32.7	4.59	37.1	269	368
6	1	1	6.55	23	0	5.03	29.8	223	5.46	40.8	4.92	32.5	250	473
6	1	2	6.47	23	0	5.09	32.4	225	5.36	41.2	4.97	34.3	119	344
6	2	3	6.32	22.5	0	6.32	22.5	90	5.23	33.6	4.74	35.7	224	314
8	1	1	6.38	23	0	5.09	30.2	90	5.39	44.5	4.74	35.7	149	239
8	2	2	6.68	23.5	0	6.68	23.5	253	4.93	28.4	4.61	41.9	430	683
8	2	3	6.31	22.6	0	6.31	22.6	203	5.11	34.6	4.76	38.9	155	358

Table 9. Average amount of CH_4 & CO_2 in mL for each digester



	Digester 8	Digester 6	Digester 4	Digester 2	Digester 7	Digester 5	Digester 3	Digester 3	Digester 1
CH4	3.111	0.681	13.942	0.469	0.238	0.212	0.065	0.018	0.018
CO2	61.394	44.276	71.561	34.086	20.981	21.927	1.394	0.416	0.322

BIOGRAPHICAL SKETCH

Shakira McCall is a graduating Master's of Science student in Engineering at Arizona State University. She is also a recent recipient of the IGERT-SUN Traineeship funded by the National Science Foundation. Her PhD work will be continued in the School of Sustainable Engineering and the Built Environment beginning Fall 2014.