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Towards a Diverse Next-Generation Energy Workforce: Teaching Artificial Photosynthesis and Electrochemistry in Elementary Schools through Active Learning

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1. Abstract

Artificial photosynthesis is a promising approach to generate commodity chemicals using abundant chemical feedstocks and renewable energy sources. Despite its importance, affordable and effective hands-on classroom activities that demonstrate artificial photosynthesis and teach key concepts, especially for primary school students, are lacking. Educating young students on this topic is a critical step in the development of the next-generation energy workforce, especially one that is diverse in race and gender. We hypothesize that an effective approach to educate a broad range of young students on the topic of artificial photosynthesis is through the use of an active learning-based lesson plan that employs cheap and accessible materials. This hypothesis is confirmed by evaluating the understanding of 5th grade students with a survey before and after a lesson plan on artificial photosynthesis that uses active-learning techniques and uses safe and highly accessible materials (baking soda, tap water, plastic jars, Ni coil, alligator clips, and a solar cell) to perform solar-powered water splitting. The lesson plan and survey questions are designed to align with the educational outcomes for 5th grade classrooms in California and to address four general learning objectives: 1) Motivations of Artificial Photosynthesis, 2) Applications of Artificial Photosynthesis, 3) Inputs and Outputs of Artificial Photosynthesis, and 4) Engineering Design for Artificial Photosynthesis. The survey data demonstrates a statistically significant improvement in overall student understanding from the lesson plan. Importantly, the data shows that the lesson plan presented here is effective at narrowing the performance gap between minority students and overly represented groups.

2. Introduction

In response to global climate change concerns, minimizing reliance on fossil fuels and increasing the use of renewable energy sources is urgently needed.[1,2] Solar-powered electrolysis can help achieve this by converting sunlight and abundant feedstocks (*i.e.*, H_2O and CO_2) into energy-dense fuels and commodity chemicals.[2,3] At the current stage in the development of these devices, the most viable architecture uses a photovoltaic (PV) cell externally wired to an electrolyzer (referred to as a PV-E system),[3] which have been demonstrated to achieve efficiencies that are economically viable.[4–8] Thus, this artificial photosynthetic process holds promise to help curb the deleterious effects of climate change and create a sustainable society.

Natural photosynthesis converts sunlight, water, and carbon dioxide into carbohydrates and oxygen.[9] Artificial photosynthesis mimics natural photosynthesis by converting the same feedstocks but into more industrially relevant chemicals (*i.e.*, H_2, CO, HCOOH, C_2H_4, C_2H_5OH, etc.) (**Figure 1**).[9,10] Water splitting is the simplest artificial photosynthesis reaction in which H_2 and O_2 gases are the products and water alone is the starting material.[11] H_2 gas is particularly relevant for fuel cells, ammonia synthesis, and plastics manufacturing, and O_2 gas is useful for medical needs.[12–16] Despite its importance and relative simplicity, affordable and effective lesson plans on artificial photosynthetic water splitting are lacking, especially for primary school students, which hinders the development of a diverse next-generation energy workforce.

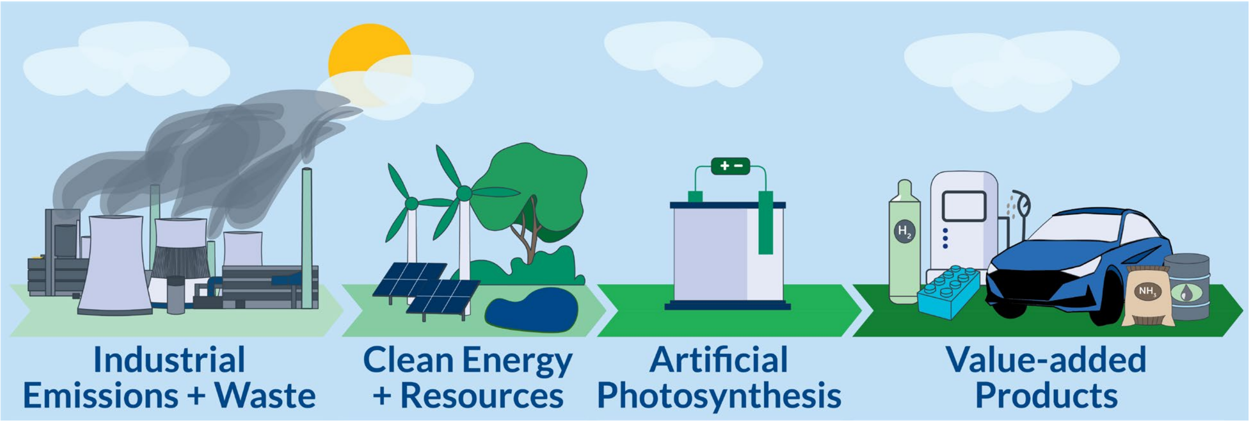

Figure 1: Illustration of artificial photosynthesis. Industrial emissions and/or waste, alongside renewable resources such as seawater, are converted using renewably generated electricity into value-added chemical commodities and fuels using an electrochemical synthesis device.

The two strongest predictors of students pursuing a career in science, technology, engineering, and/or mathematics (STEM) are academic proficiency and STEM competency.[17] This finding is supported by recent work which shows that the performance of first graders on the science and math sections of a general knowledge exam is more predictive of STEM achievement in secondary school than measures of success in other subjects or of the students' backgrounds.[18] Thus, improving student performance and understanding on STEM subjects during primary school is expected to facilitate students' pursuit of careers in STEM.[19,20] The majority of STEM-related careers that current primary school students will pursue is predicted by the U.S. Department of Labor to not currently exist.[21] This prediction motivates the need for implementing lesson plans on current leading research topics to foster an excitement in K-12 students about STEM and an understanding of STEM subjects, which should aid the development of the next-generation workforce.

With the current state of education, future STEM-related careers will not be equally accessible to everyone because of low university enrollment and retention of racial minorities and women in STEM fields,[22] of which a primary contributor is the inadequate preparation in K-12 on STEM-related subjects.[23] Potentially potent methods for improving STEM education in K-12 are the use of peer collaboration and research experience, as concluded by a comprehensive review of STEM programs.[23] Thus, active-learning techniques that employ student teamwork and experimentation could be an effective strategy to educate a diverse range of students on the topic of artificial photosynthesis. Several previous studies have confirmed that hands-on, active learning experiences are successful at educating students on STEM subjects.[24–29] These studies have shown that active learning pedagogies are effective at narrowing the performance gap between racial minorities and overly-represented groups. Understanding whether the same impact on performance gap can be achieved with an active learning-based lesson plan on artificial photosynthesis for primary school students will be important for the development of a future energy workforce that is demographically diverse.

Past efforts involving artificial photosynthesis lesson plans have been typically conducted with college chemistry undergraduate students and are not translated across other disciplines and younger students.[30–33] These studies also lack demographic data on the students participating in these lessons, which leads to speculative conclusions on the efficacy of the lesson plan across demographics. Lastly, electrochemistry classroom kits generally use expensive, hard-to-obtain materials, such as polymeric ion-exchange membranes and precious metal electrodes, and inaccessible laboratory equipment (*e.g.*, potentiostat or product quantification tools).[30] Many of the kits on the market cost more than $100 per unit and do not allow for hands-on student interaction during the assembly of the cell;[34–36] see **Table S1** for a list of available solar electrolysis kits on the current market. This high cost is also prohibitive for poorly funded schools, which tend to have high enrollment of racial minorities,[23] and are likely too costly for use in 2nd and 3rd world countries. To prepare the future energy workforce, students of all backgrounds should be introduced to artificial photosynthesis with hands-on lessons that employ active learning early in their education.

The topic of artificial photosynthesis and electrochemistry is quite compatible with the present educational goals of 5th grade science classrooms in California. **Figure 2** presents a schematic depiction of the current topics in the 5th grade science curriculum. 5th grade is a particularly useful time to introduce concepts within artificial photosynthesis, as it is when students are taught the topic of natural photosynthesis. Additionally, the emphasis on energy flows and engineering design lends themselves well to a hands-on lesson where students build their own PV-E device. All considered, there is a great opportunity for the introduction of 5th grade students to high-level concepts of electrochemistry with practical application. Introducing students to concepts of electrochemistry earlier in their education via active learning will be impactful for preparing the next-generation workforce.

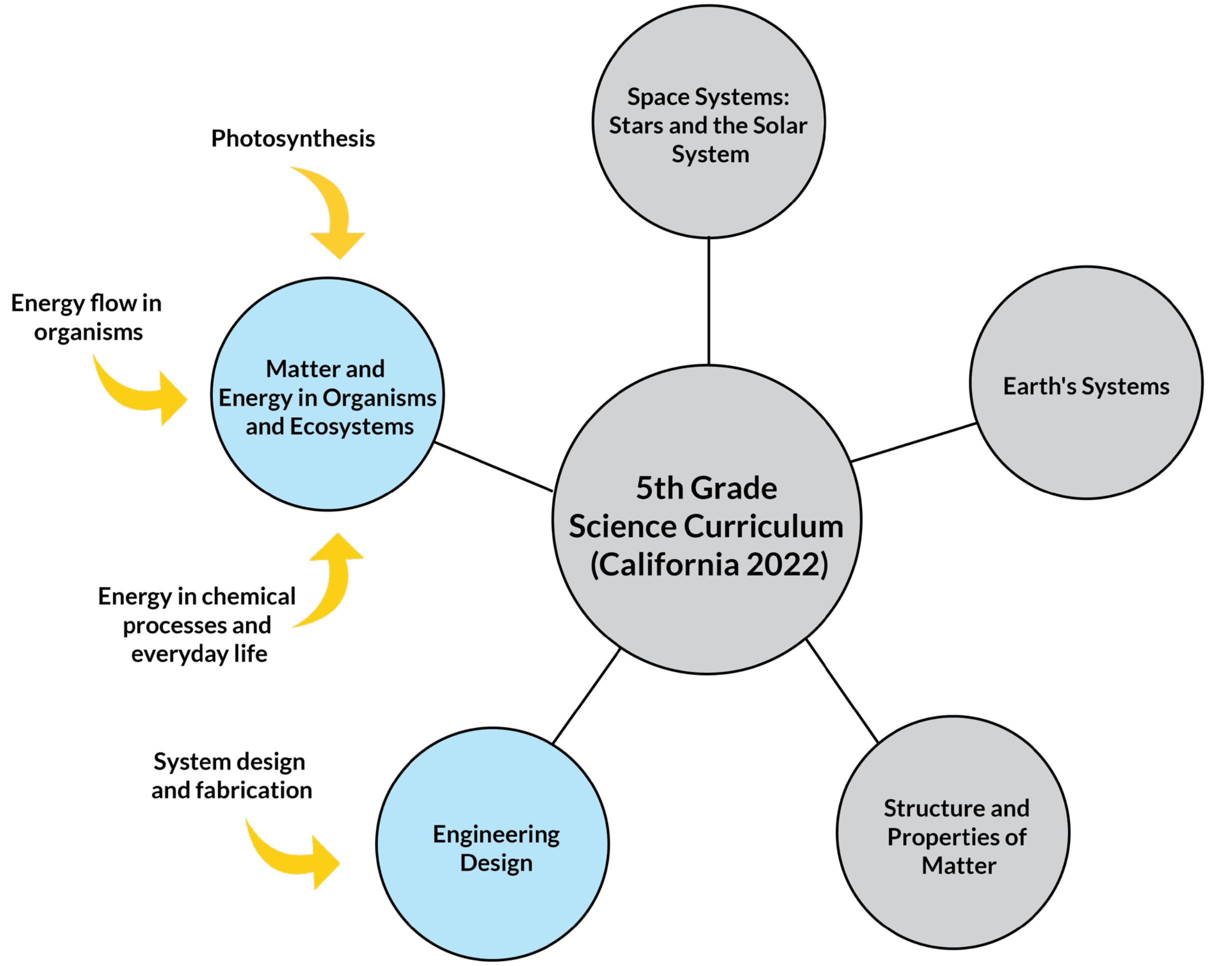

Figure 2: Depiction of 5th Grade Science curriculum as outlined by California Department of Education.[27] Blue nodes with yellow arrows denote areas in which electrochemistry and artificial photosynthesis easily slot into the current science curriculum.

This work presents a simple and inexpensive lesson for demonstrating the general principles of artificial photosynthetic water splitting to primary school students. The lesson plan focuses on teaching the motivations, applications, inputs and outputs, and engineering design of artificial photosynthesis devices through an engaging, student-run demonstration of solar-powered water splitting. The present study improves on prior artificial photosynthesis lesson plans by employing safe and highly accessible materials, as well as ascertaining the efficacy of the lesson plan for teaching basic concepts of artificial photosynthesis in diverse classrooms via data from pre- and post-surveys. With these data, we confirm a statistically significant improvement in student understanding and find the lesson plan narrows the performance gap between minority students and overly represented groups. These results confirm the hypothesis that an active learning-based lesson plan on artificial photosynthesis that employs cheap and accessible materials is effective at educating a diverse range of students. This study provides a key step forward in the development and education of a demographically diverse energy workforce for addressing one of society's most pressing challenges.

3. Methods

3.1 Learning Objectives for a 5th Grade Artificial Photosynthesis Lesson

The research question pursued in this study is whether 5th grade students who have very limited, if any, experience with the concepts of artificial photosynthesis can learn about this subject effectively based on an active learning lesson plan that uses cheap and accessible materials. The effectiveness of the lesson plan is evaluated based on student understanding of four high-level learning objectives, which are 1) Motivations of Artificial Photosynthesis, 2) Applications of Artificial Photosynthesis, 3) Inputs and Outputs of Artificial Photosynthesis, and 4) Engineering Design for Artificial Photosynthesis. The primary student outcomes of the lesson plan are detailed in the following subsections on each of the main learning objectives. The detailed governing physical principles and reactor engineering of a solar water splitting device are far too advanced for 5th grade students, and, hence, are not included as a learning objective.

However, they are provided in **Supporting Information Section S2** for those who are interested in understanding these details.

3.1.1 Principles of Artificial Photosynthesis

After participating in the lesson students should be able to appreciate and understand the motivations for developing artificial photosynthesis technologies. The students should identify that these technologies allow for the **conversion of abundant renewable resources** into **value-added products** using **sustainable energy**. Additionally, the students should be able to draw comparisons between **natural** and **artificial** photosynthesis, noting that natural and artificial photosynthesis **both involve** the **conversion of solar energy to make value-added products**. However, the difference between the two is that artificial photosynthesis technologies are **fully manmade, do not involve living organisms, and can generate a variety of products**. Lastly, students should recognize that solar radiation is a **clean energy source** and, hence, using artificial photosynthesis is **better for the environment** than traditional manufacturing processes.

3.1.2 Applications of Artificial Photosynthesis

Once students are introduced to the principles of and motivations for artificial photosynthesis, they should be able to explore **specific applications** of artificial photosynthesis for the formation of products such as **plastics, fertilizers, and fuels**. They should understand that plastics are used to make a variety of useful and fun items, such as the toys they play with. Moreover, students should learn that fertilizers are critical chemicals for growing crops and that fuels are needed for on-demand energy. After the artificial photosynthesis activity, students will consider how to use the hydrogen and oxygen gas generated in the solar water splitting experiment. Particularly, students explore how **hydrogen** can be used as a **fuel** to generate energy for powering vehicles and/or facilities and how **oxygen** can be used for **breathing air** when scuba diving and during space travel and colonization. Hydrogen and oxygen gases are also relevant in the chemical and medical industries as a chemical precursor and for oxygen tanks, respectively. However, we choose to focus the students' attention on applications that are more understandable and that are more likely to spark their imagination.

3.1.3 Inputs and Outputs of Artificial Photosynthesis

From the lesson plan, students should understand that **inputs** into the solar water-splitting system are **sunlight** and **water**, and the **outputs** are **hydrogen** and **oxygen** gases. We highlight that water is **two parts hydrogen** and **one parts oxygen** (i.e., "H-two, O"), so twice as much hydrogen will be made as oxygen. This helps students to understand why there are more bubbles evolving off one electrode than the other. In a typical general chemistry classroom, this concept would be introduced as stoichiometry. But for the purposes of a 5th grade classroom, a high-level understanding of the inputs and outputs of the system is sufficient.

3.1.4 Components of Artificial Photosynthesis

By the end of the lesson, students should be able to **identify the components** of the solar water splitting device and **identify their function**. They should recognize that the **solar cell absorbs** the **sunlight** and **converts it into electricity**, and that the **electrolyzer** takes that **electricity** and uses it to **split water into hydrogen and oxygen**. Additionally, students should understand that hydrogen forms at one electrode and oxygen forms at the other.

3.2 Survey Development

To assess students learning from the lesson plan, a written survey was developed. Students were assessed before and after the lesson to determine the impact of the lesson on student knowledge and understanding of the high-level learning objectives. This survey can be found in **Section S3.1**. The contents of the pre- and post-survey are identical and consist of questions related to the basics of artificial photosynthesis, solar cells, and water splitting. This survey has been approved by the Institutional Review Board (IRB) at the Lawrence Berkeley National Laboratory, and parental assent and student consent was obtained for participation in the educational study.

Great care was taken to ensure the contents of the survey evaluated the key learning objectives outlined in **Section 3.1** and that the survey content fit within the current educational outcomes outlined by California curriculum standards. As seen in **Figure 3**, each question on the survey can be assigned to one or more of the key learning objectives of the study (**Figure 3a**) and correspondingly fits into one or more California 5th-grade science curriculum modules (Matter and its Interactions, Earth and Human Activity, Energy, or Engineering Design) (**Figure 3b**). Greater detail regarding the choice of questions and how they reflect understanding of the lesson objectives and their fit within California curriculum modules can be found in **Supporting Information Section S3.2.**

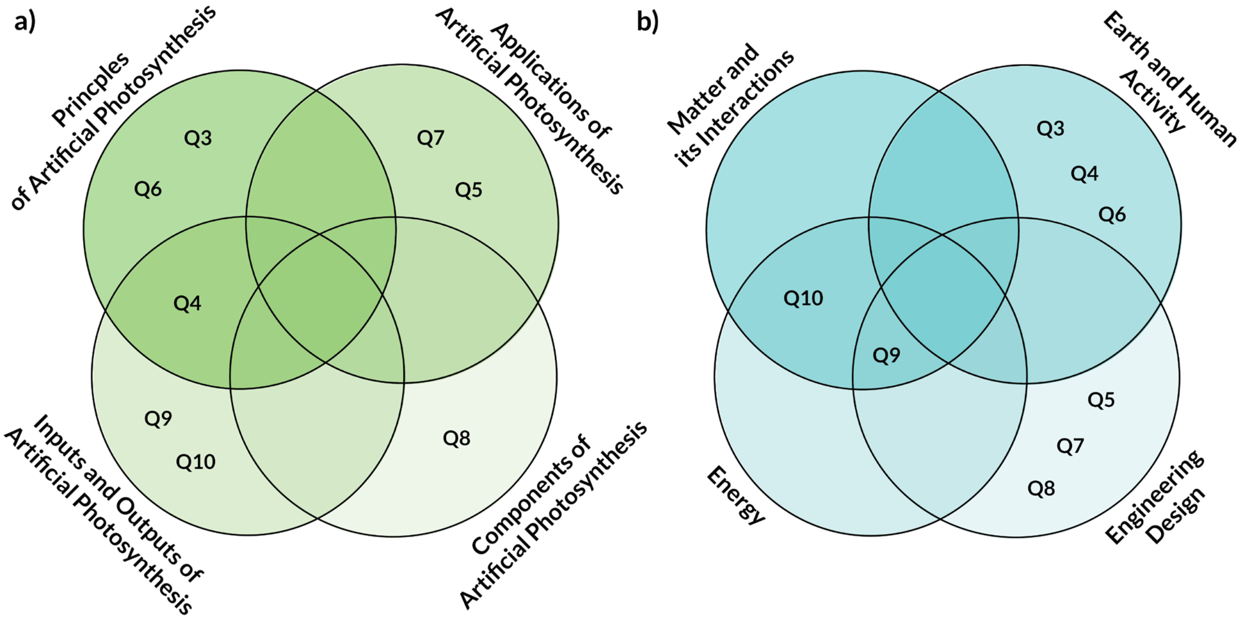

Figure 3: Survey questions categorized by their corresponding **(a)** lesson objectives as detailed in **Section S3.1** and **(b)** by their adherence to learning outcomes outlined by the California 5th-grade science curriculum.

3.3 Lesson Plans and Materials

3.3.1 Lesson Overview and Timeline

Figure 4 displays a timeline of the lesson and surveys. Students first completed the written pre-lab survey described in **Section S3.1**, which took about 10 minutes for a 5th grade classroom to complete. After the pre-survey, the lesson consists of two parts: a short lecture on artificial photosynthesis, followed by a hands-on experiment involving the assembly of a PV-E device. The introductory lecture was approximately 10 minutes, and during this time students were encouraged to participate in the discussion and answer questions as prompted by the instructor. Afterwards, the students were paired in groups of two or three to build and test the artificial photosynthesis device. The cell took approximately 15 minutes to build, and a 5-minute period was allotted for students to bring the cell into the sunlight, record their observations, and discuss their observations with their group. Following the experiment, the instructor(s) facilitated a brief class reflection and discussion for 10 minutes. Students then completed the post-lab assessment in approximately 5 minutes. Overall, the total time for the lesson and surveys was approximately an hour (*i.e.*, a single class period for a 5th grade classroom).

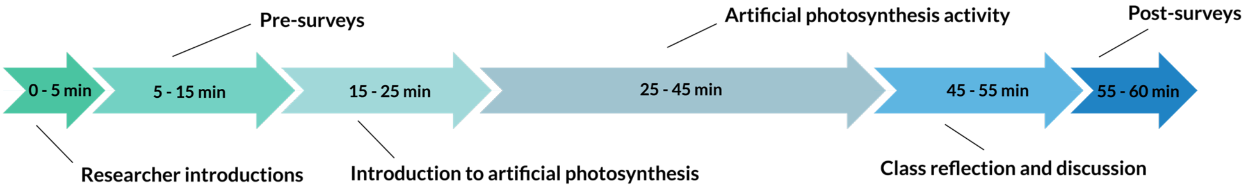

Figure 4: Timeline of artificial photosynthesis lesson including researcher introductions, pre-surveys, introduction to artificial photosynthesis, artificial photosynthesis activity, class reflection and discussion, and post-surveys.

3.3.2 Lesson Materials and Methods

The lecture on artificial photosynthesis was supplemented with a slideshow presentation that introduces concepts of natural photosynthesis and the definition of artificial, and subsequently combines the two ideas to explain artificial photosynthesis. The slide deck can be found in **Section S4**. The instructor provided examples of artificial photosynthesis products, such as plastics and fuels, before transitioning into building the PV-E device.

This experiment was designed to be completed in groups of one to three, depending on the class size and capacity. The lesson can be performed in a standard elementary school classroom and does not require a laboratory bench or fume hood. Students should be familiar with (or need to be taught) standard science safety procedures and how to safely handle equipment and materials. Detailed step-by-step instructions for the building process are provided in the Student Worksheet and were handed out to each group of students. The Student Worksheet can be found in **Section S5**.

First the students received a plastic jar (Hajoyful; Amazon) containing all their materials for the lesson (**Figure 5**). The jar serves as the chassis for the electrolyzer and contains Ni wire coils (TEMCo; Amazon), alligator clips (WGGE; Amazon), 15 mg of Baking Soda (Arm & Hammer) packaged in a Ziploc bag, and a monocrystalline PV-cell (digi-Key) (for a complete bill of materials see **Table S2 in Section S6**). The total cost of a single kit is $ 8.17 before tax. The low cost of this kit makes it highly advantageous compared to other kits currently on the market (**Table S1**), especially when considering their use in public schools with low funding or for outreach to 2nd and 3rd world countries. The lid of the jar has two holes drilled manually to allow for the insertion of the Ni coil electrodes. The contents were emptied from the cell. The baking soda was poured into the jar, and then the jar was filled with tap water to a black line that was marked by the instructors with a sharpie before the lesson (at a level of ~ 300 mL). The Ni coils were then inserted through the holes in the lid and the lid was screwed on to the jar, making sure that the Ni coils do not physically touch to avoid short-circuiting the cell. Lastly, alligator clips were used to connect the electrolyzer to the PV-cell.

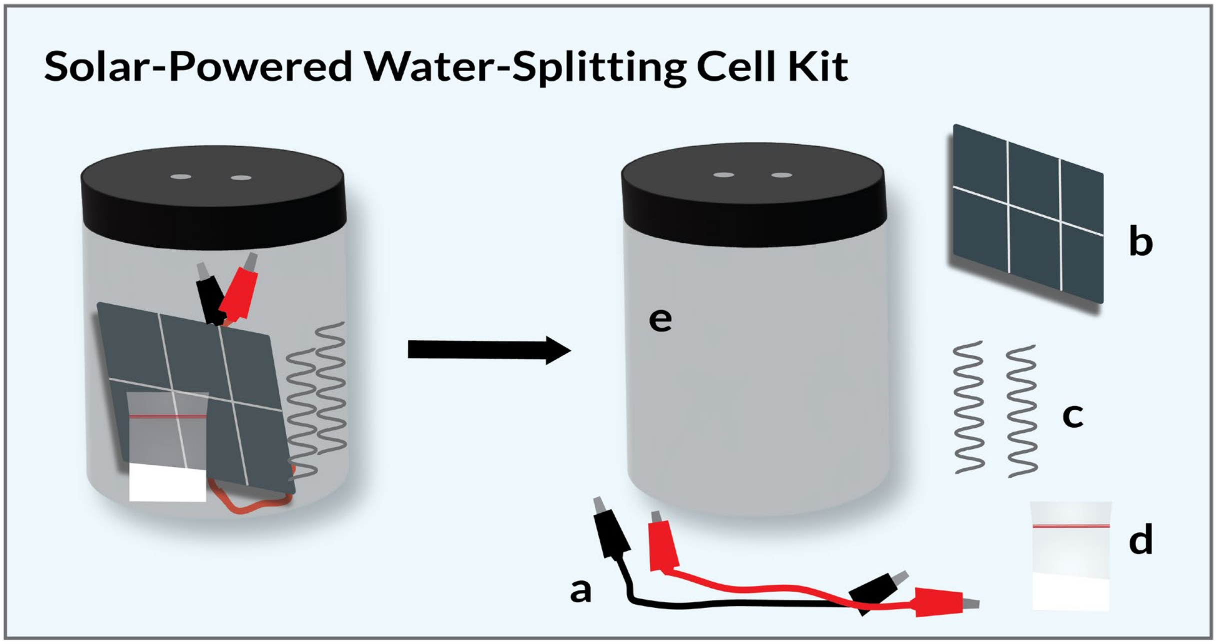

Figure 5: Materials provided for the construction of solar-powered water-splitting cells: (a) alligator clips (b) monocrystalline PV-cell (c) nickel wires (d) baking soda (e) plastic jar.

Once the cell was assembled, students took it outside and brought it into the sunlight. If the classroom has ample sunlight, then taking the cells near the window also suffices. Students observed bubbles forming on the two electrodes, with significantly more on the cathode than the anode (**Figure 6**). The instructors posed questions to the students to engage learning (*i.e.*, what electrode produces more bubbles, why is one electrode bubbling more than the other, which electrodes produce hydrogen and oxygen, what happens when the PV-cell is covered, etc.). Students discussed these questions in their groups before the class was brought back inside for a class-wide discussion of their results. During this period, instructor(s) explained the overall reactions taking place and the inputs and outputs of the process.

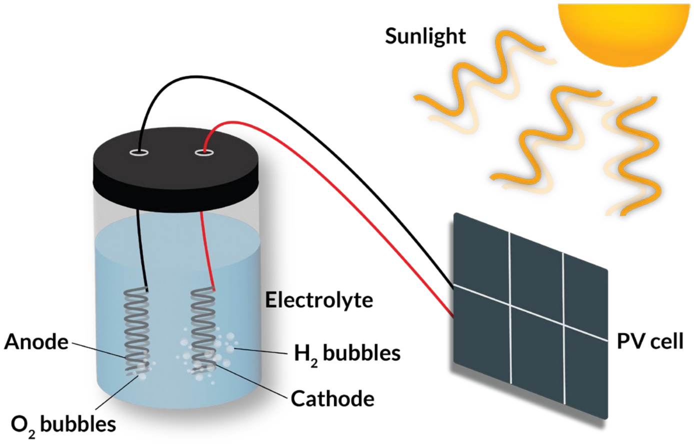

Figure 6: Schematic of assembled solar water splitting device in operation.

3.3.3 Lesson Hazards

Some aspects of the laboratory experiment have risks, such as using solar-generated electricity and producing hydrogen gas. Producing a mixture of H_2 and O_2 can be hazardous, but the volumetric rate of H_2 generation is so small (< 1 mL min^{-1}) that the potential risks are minimal. Moreover, the electricity used is not greater than that produced by 4 AA Batteries and does not require wall plugs, and the chemicals involved are solely tap water and baking soda.

3.3.4 Potential Lesson Extensions

Extensions of the lessons could include: employing pH indicators or dyes to better observe the generation and consumption of ions in solution, wiring multiple solar cells in series or parallel to demonstrate how photovoltage and photocurrent change rates of bubbling, or explicitly studying the effect of solar insolation angle on the rate of bubbling at the electrodes. Additionally, this lesson plan can be extended to 6th and 7th grade education by incorporating multimeters to measure the electrical current passing through the cell and calculating the amount of hydrogen produced using Faraday's Law. Members of our group have also adapted the lesson plan to incorporate the effect of wiring additional solar cells in parallel or in series with the electrolysis unit in order to observe the change in voltage across or current through the electrolyzer, as well as changes in the rate of bubbling. These additions make this lesson plan amenable to middle school or early high school-age students, showing that the topics and principles demonstrated here are applicable to a wide range of age groups.

4. Results and Discussion

4.1 Instruction and Student Engagement

The lesson was taught across four 5th grade classrooms in Oakland, CA, reaching approximately 100 students. Of those students, 43 students participated in the pre-survey, and 41 of those 43 students participated in the post-survey (resulting in a total response rate ~ 40%). Throughout the course of the lesson, the students were highly interested in the material presented on the slide deck and asked a plethora of well-formed questions that indicated engagement in the lesson. For lesson periods where there was more time, the instructors talked with the students about how artificial photosynthesis could help enable the development of a colony on Mars.[37] For this question, there was substantial engagement from the students, with students discussing how the O_2 generated via electrolysis could help these imagined astronauts breathe, and the H_2 could assist in providing fuel.

Once the slide deck was thoroughly discussed, the students were instructed on how to assemble their artificial photosynthesis kits, following the steps outlined in the **Methods** section and the handout in **Section S5**. Most students were able to assemble the kit without substantial assistance from the instructors. When the instructors did intervene, it was most commonly to disentangle the anode and cathode coils. Many students experienced a momentary lack of electrolysis, due to short circuiting, while the two electrodes were in contact. This is an artifact of not employing a separator between the two electrodes, which brought down the cost significantly compared to kits that employ solid polymer membranes.[34–36] However, future improvements on the kit could seek to resolve the issue of shorting by using more rigid mesh electrodes as opposed to Ni wire coils or using two separate chambers connected by a salt bridge. A porous plastic mesh placed in between the two coils that inhibits their electrical contact while still allowing for solution contact could also resolve this issue. Any solution, however, will raise the cost of the kit beyond the $8.17 per unit of our current kit (**Section S6**). These cost considerations will have to be made on a per-classroom basis based on the available funding.

When the device was taken outside, every student did indeed observe bubbling of H_2 and O_2 on the cathode and anode, respectively, as shown in **Supporting Video 1**. The bubbling was quite visible and intense when the solar panels were pointed directly at the sun, and the students observed that covering the solar panels or pointing them away from the sun resulted in termination of the bubbling due to a lack of illumination on the Si solar cell. Overall, the students were engaged throughout the process of the slides, building the cell, and taking it into the sun and observing electrolysis. On average the lesson took 45 minutes to complete without the pre- and post-survey.

4.2 Qualitative Student Answers

Throughout the lecture portion of the lesson, the following questions were asked by the instructors:

1. What are some examples of things that are artificial and what does artificial mean?
2. What do plants need to survive?
3. What are some cool and useful products that can be made with artificial photosynthesis?

i) Some examples provided in response to Question 1 include: “turf,” “artificial wombs,” “artificial flavoring,” and “fake meat.” For definitions, students generally provided the definition that artificial meant something “fake” or “manmade.” Importantly, while not all students initially knew the definition of “artificial,” upon ensuring adequate wait time and facilitating the opportunity for students to actively discuss with their peers, students generally came to a consensus on the meaning of the word artificial and provide well-formed examples.

ii) In response to Question 2, students responded with “water, sunlight, soil, air, and carbon dioxide.” For this response, it was clear that the students had previously learned about natural photosynthesis and were able to call upon this knowledge from their prior coursework.

iii) For Question 3, the students provided cogent examples of sustainable energy technologies and items for which they hoped to produce via artificial photosynthesis, such as “toys” and “fuels.” Other responses included “a new species,” “a whole city,” “artificial plants,” “gold,” and “energy to turn mud into bricks for houses,” among many other responses. Notably, some items such as “gold” or “a new species” cannot be made with artificial photosynthesis because these are not composed of or require more complexity than the standard chemical building blocks of carbon, hydrogen, oxygen, and nitrogen employed in artificial photosynthesis. Nonetheless, the instructors encouraged out-of-the-box thinking from the students to spark imagination. A subsequent slide on items that have already been made with artificial photosynthesis, such as fertilizers, fuels, and plastics, demonstrates what is possible with the current state of the technology.

For the experiential portion of the lesson, the students were asked to comment on what they observed during the experiment. Some example responses included:

1. "One electrode bubbles more than the other."
2. "One electrode turned green."
3. "Pointing the solar cell away from the sun made the bubbling stop."

The instructors then proceeded to ask follow-up questions about these observations to further engage and teach the students.

i) Regarding the fact that one electrode bubbles more than the other, the instructors explained this by drawing a cartoon structure of a water molecule and asking the students what the drawing was. Some students identified the drawing as "Mickey Mouse," but quickly the classrooms had properly identified the molecule as water. At this point, the instructors highlighted that water is two parts hydrogen and one part oxygen; so, the cathode, which makes hydrogen, bubbles twice as much as the anode, which makes oxygen. This engagement helped cement the concept that water was being split into hydrogen and oxygen and introduced these students to the concept of stoichiometry.

ii) With respect to the change in color of the oxygen evolving anode, this change in color occurred because some degree of Ni corrosion took place at the anode, wherein the color of the electrode turned to black due to the formation of NiOOH,[38] and some Ni ions were released into solution resulting in a slight color change of the electrolyte in the vicinity of the anode to a murky green or yellow color. To teach this concept, the instructors asked the students what happens when metals are exposed to air or oxygen for long periods of time, referring to how the Statue of Liberty or metal screws change color over time. The students quickly responded with "rusting" or even in some cases, "oxidation." The instructors then connected the change in color of the Ni anode to rusting students observe in their everyday lives, stating that the oxygen formed during water splitting speeds up the "rusting" of the Ni anode.

iii) Lastly, regarding the cessation of bubbling when the solar cell was covered or turned away from the sun, the instructors asked the students what powers the water splitting reaction. The students answered that the sun powers the reaction. The instructors responded that the solar cell converts the sun's energy to electricity that can be used in the reaction, so if the solar cell cannot absorb the sun's energy, the reaction stops.

All told, the students were highly engaged in the lesson and provided excellent responses to instructor-led questioning that led to fruitful and thoughtful follow-up questioning.

4.3 Qualitative Student Questions

Along with their responses to our qualitative questioning, the students also asked incredibly perceptive questions for their age group. Three of the most commonly questions asked were:

1. "What does the baking soda do?"
2. "Why does hydrogen form at one electrode and oxygen at the other?"
3. "Can we break down carbon dioxide like we break down water?"

i) To answer the question regarding the role of the baking soda, the authors note that the concept of ions and electrolytes is too advanced for a 5th grade audience, so instead, the instructors stated the baking soda helps to "complete the circuit" between the two electrodes.

ii) Regarding why the two electrodes perform different reactions, we note that the concept of reduction-oxidation reactions is beyond the scope of 5th grade learning. However, to answer the posed question, the instructors noted that the two electrodes in the electrolyzer are similar to the positive and negative ends of a household battery. We said that because one electrode is positive and the other is negative that they perform different chemical reactions. The negative electrode makes hydrogen because that reaction consumes electrons, and the positive electrode makes oxygen because that reaction generates electrons.

iii) To answer the question about the electrolysis of carbon dioxide, the authors responded that carbon dioxide electrolysis is a technology actively in development. The instructors note that carbon dioxide electrolyzers are similar to the water electrolyzer tested by students, but instead of using baking soda and water, researchers use baking soda and "sparkling water," *i.e.,* a bicarbonate electrolyte with carbon dioxide bubbled into it. We noted that carbon dioxide bubbled into the water can react to form the carbon-containing products that make up plastics and toys mentioned in the lecture.

4.4 Student Assessment and Lesson Efficacy

To evaluate the efficacy of the lesson, the results of the pre-survey and post-survey are analyzed to understand how the distribution of scores (between 0 and 8) changed upon the execution of the developed lesson and to determine the statistical significance of changes between the pre- and post- survey data. **Figure 7a** shows that the pre-survey scores have a sharp peak around 4 out of 8, whereas the post-survey scores have a broad peak around 7 out of 8. Additionally, the mean score of the pre-survey is 50% (4 out of 8), and for the post-survey it is 75% (6 out of 8), as seen in **Figure 7b.** To confirm that the changes in the distribution and the average are statistically significant, a *t*-test is performed on the pre- and post- survey data, and the test confirms strong statistical significance (**Table S3;** p-value = 3.29×10^{-7}).

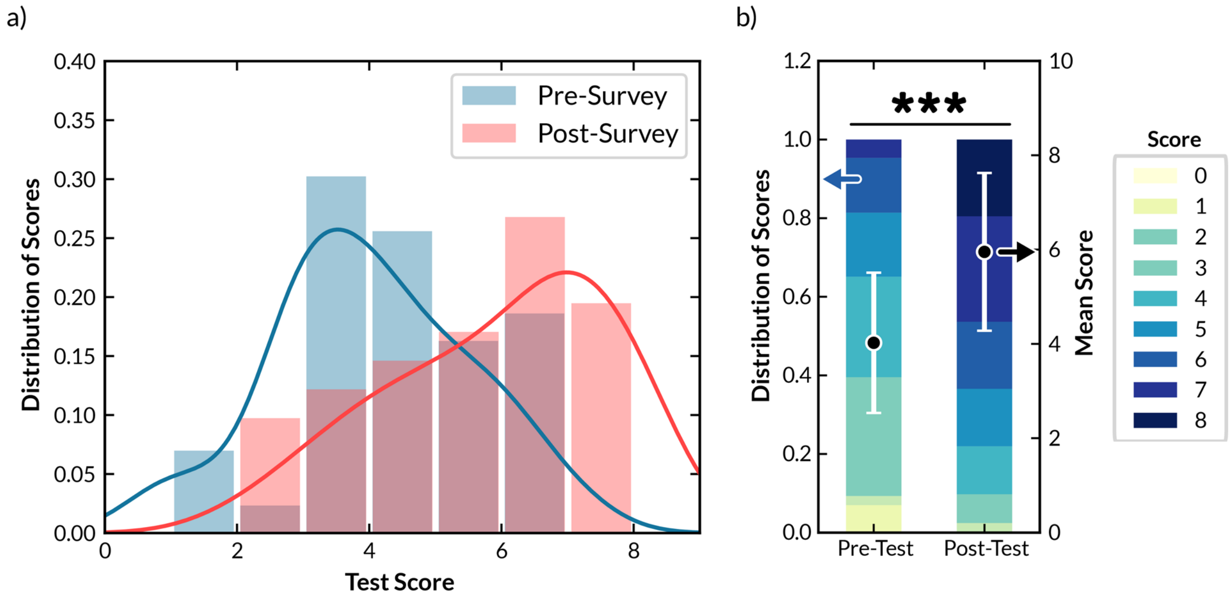

Figure 7: (a) Distributions of survey scores of the pre-survey (blue distribution) and post-survey (red distribution). **(b)** Stacked bar plot displaying distribution of scores and change in mean score during pre- and post- testing. Asterisk denotes the level of statistical significance. (***) denotes $p < 0.001$.

Furthermore, when considering data solely from individual classrooms, the first, third, and fourth classrooms each exhibit a statistically significant improvement in the performance of the students **(Figure S4**). It is important to note, however, that due to moderate return-rates of parental consent forms, each classroom only possessed a sample size on the order of 10 or so students. Lastly, when student data is aggregated into classroom averages, in which each classroom is considered a sample as opposed to considering individual students, the results still hold **(Table S5, Figure S5**); we note that it was common for a classroom to have a majority of one race, which differed between classrooms (*e.g.*, one classroom may have majority Hispanic/Latinx and another having majority Asian students). Across the four classrooms, not only did the students observe statistically significant increases in their performance, but the overall classroom averages also increased in a statistically significant manner (*p*-value = 0.029). These results indicate that a significant increase in the understanding of the general principles of artificial photosynthesis occurred as a consequence of this active learning-based lesson plan and hands-on kit, consistent with prior demonstrations of active learning principles.[27]

4.5 Effectiveness Across Student Demographics

While the overall improvements in performance observed in **Section 4.4** are impressive, a key to developing a diverse energy workforce is confirmation that the education received by K-12 students is effective in teaching students of all demographics and does not leave students of any one group behind. To confirm the effectiveness of the lesson plan and kit across various racial and gender groups, we collected demographic data of the students (**Figure 8a-b)**. Asian students are the largest group, whereas African American/Black, Hispanic/Latinx, White, and other groups have about the same number of students. Furthermore, there are slightly more male than female students. Across all these groups, there is a notable increase in scores, demonstrating the lesson plan increased students' understanding of artificial photosynthesis regardless of racial or gender identity; see **Figure 8c**. The increase in score is largest for African American/Black, Hispanic, and Asian students. Moreover, female students have a slightly higher increase in score than male students. Indeed, for nearly every demographic group for which the lesson was tested, the improvement in score due to the lesson is statistically significant, as evidenced by *t*-test **(Table S4**). The white student group is the only one that did not exhibit a statistically significant increase in score between the pre- and post-survey, although this can be explained because white students also possess the largest pre-survey average, leaving them less room for improvement in the post-survey. Furthermore, when comparing the performance gap between overly-represented (Asian and White) and under-represented (Latinx, African-American/Black, and other) students, the overly-represented students outperformed under-represented students by 0.7 points on average in the pre-survey, whereas in the post-survey this value is only 0.3 points. Critically, these results demonstrate that the active learning-based lesson plan and kit presented here is effective at narrowing the knowledge gap in students across various race and gender groups, again consistent with prior literature in active learning.[28] However, more granular data across a greater number of diverse classrooms, perhaps with a longer survey, is required to better quantify the narrowing in performance gap and establish if this change is statistically significant. Nonetheless, these improvements across all demographics represent a key step in creating the diverse energy workforce of the future.

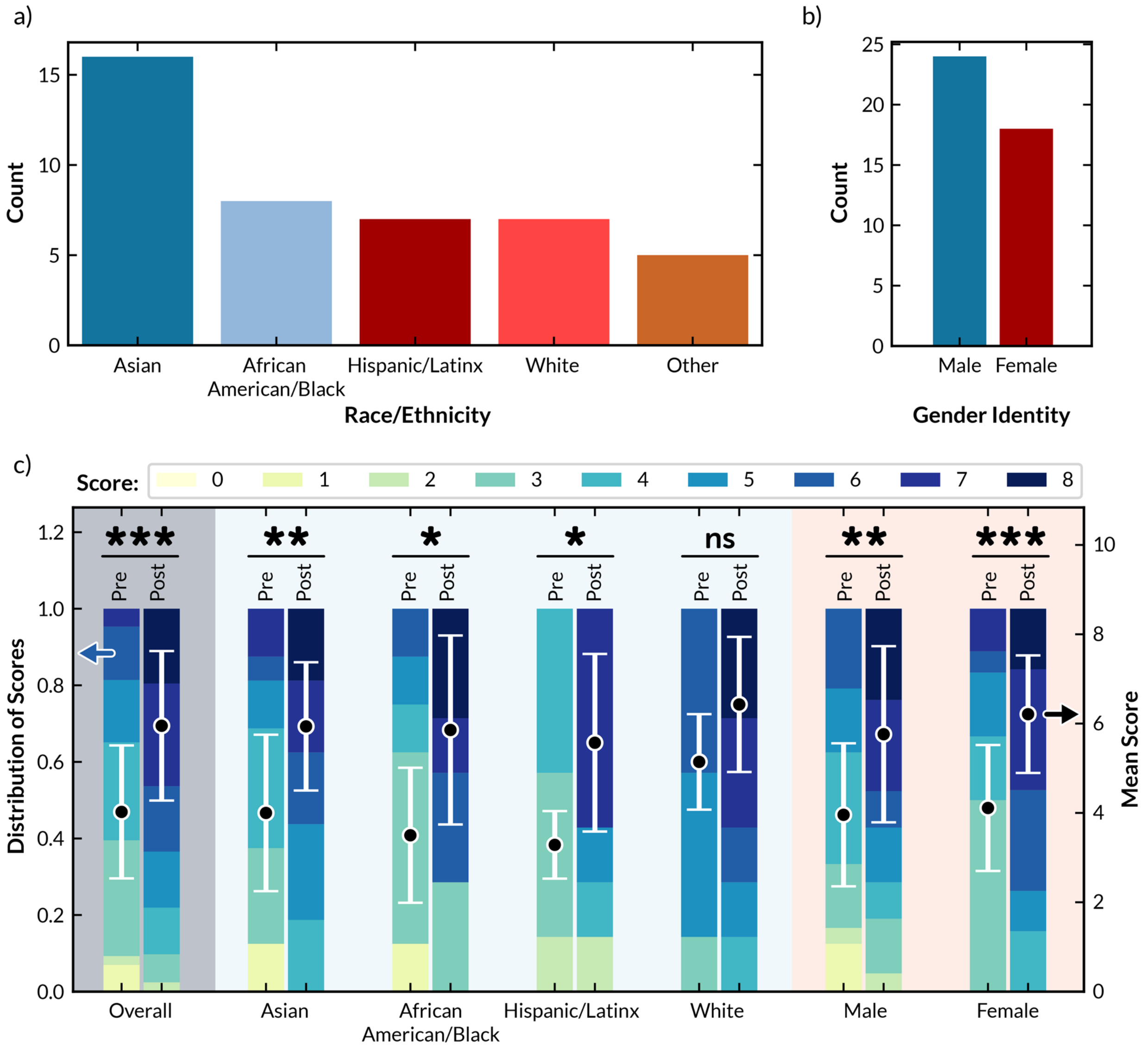

Figure 8: Bar plot of **(a)** racial demographics and **(b)** gender demographics of students surveyed in the pre- and post-surveys from **Figure** 7. **(c)** Stacked bar plot representation of grade distributions of survey scores of the pre-surveys (left) and post-surveys (right) as well as the change in the mean between the pre- and post-surveys broken down by race and gender for groups with > 5 students. Groups < 5 students were removed or aggregated into "Other" to prevent identifiability of survey-takers. Asterisk denotes the level of statistical significance. (*) denotes $0.05 > p > 0.01$, (**) denotes $0.01 > p > 0.001$, and (***) denotes $p < 0.001$. (ns) denotes a lack of a statistically significant change.

5. Conclusions

Critical to the creation of a sustainable society is educating the next-generation workforce on topics that are at the frontier of renewable energy technology. This paper outlines an educational study in which the research question under investigation is whether an active learning-based lesson plan on artificial photosynthesis that employs cheap and accessible materials is effective at educating a demographically diverse range of primary school students. A low-cost, solar-powered water splitting kit is developed (< \$10 USD) and used to teach 5th graders the principles of artificial photosynthesis. We employ simple, easily accessible components (plastic jars, nickel wires, baking soda, tap water, and alligator clips) to allow students to build their own solar-powered water electrolyzer. A survey is developed that assesses student understanding on high-level learning objectives related to the topic of artificial photosynthesis. By collecting pre- and post-survey data, the efficacy of the kit and the lesson plan for various racial and gender groups is confirmed. The data shows a statistically significant improvement (p-value = 3.29×10^{-7}) in overall student learning. Moreover, all race and gender groups studied exhibit a statistically significant increase in survey score, except for white students because of their high pre-survey score. Importantly, we find that for all racial and gender groups the post-survey scores is nearly the same, demonstrating that the active learning-based lesson plan and kit presented here helps to reduce knowledge gaps between demographic groups. In future studies, this lesson plan can be extended to higher levels of education by incorporating multimeters to measure the electrical current passing through the cell and calculating the amount of hydrogen produced using Faraday's Laws. This study provides a cost-effective and tested approach for educating students of various backgrounds, a critical step for the development of a diverse, future energy workforce.

6. Supporting Information

Kit comparison; principles of artificial photosynthesis; survey questions; lesson slide deck; student worksheet; bill of materials; t-score breakdown; video.

7. Notes

The authors declare no competing financial interest.

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Data Availability

While the unprocessed student data is protected by confidentiality, the processed data used to create the figures shown in the manuscript and supporting information have been uploaded to Zenodo and can be accessed at the following DOI: 10.5281/zenodo.7582666.

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