Supporting Information

Teaching Electrochemical Energy Conversion and Storage Through Active Learning: Insights from Science Workshops

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Electrochemistry: How do we transform energy?
Detailed Workshop Plan

Course Summary

Did you know that electrons are the unsung heroes powering our world? From the smartphone in your pocket to cutting-edge spaceships, electrons produced by chemical reactions shape our lives. But what is the connection between chemistry and electricity? And what breakthrough technologies will reshape our future over the next half-century? Dive into these intriguing questions with our workshop on electrochemistry!

We will explore the fundamental principles behind the technologies we use every day. You will learn how the material's properties impact the performance of various electrochemical devices. Then, get hands-on experience as you test real electrolyzers, fuel cells, and high-density aluminum batteries, bringing theory to life. Join this workshop and embark on a fascinating journey to discover how electrochemistry is revolutionizing our world, one electron at a time!

General Learning Outcomes

- Students will identify the main components and operating principles of three electrochemical energy conversion and storage technologies: water electrolyzers, fuel cells, and batteries.
- Students will describe the underlying phenomena by which water electrolyzers, fuel cells, and batteries convert or store energy, focusing on the symbolic and particulate levels.
- Students will construct a functional electrochemical energy device using affordable materials.
- Students will operate electrochemical energy devices and the instruments necessary to conduct appropriate measurements at the macroscopic level correctly.
- Students will evaluate the influence of operational conditions on the performance of a functional electrochemical energy device.
- Students will contrast the advantages, limitations, and applications of water electrolyzers, fuel cells, and batteries.
- Students will recognize the role of electrochemical energy conversion and storage technologies in mitigating climate change and promoting sustainability in society.
- Students will justify using electrochemical energy technologies to decarbonize industry and society.

Instructors

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Table of Contents

Workshop Description

Course Overview and Philosophy

This workshop was designed for the Clubes de Ciencia MX (CdeCMx) initiative to deliver a stimulating STEM experience to young students. CdeCMx is a non-profit organization offering free extracurricular STEM opportunities to secondary and tertiary students. CdeCMx courses and programs are designed to inspire and motivate students towards STEM careers, enhance access to scientific education with the latest research advances, and foster collaborative networks between students and institutions in Mexico and the United States. These programs are designed and implemented by young scientists, including graduate students, postdoctoral researchers, and early career faculty from top institutes.

Instructors interested in participating craft a workshop proposal based on their technical expertise and submit it to the annual CdeCMx call. The workshop is assigned to a specific city in partnership with local institutions upon approval. We implemented our workshop in Chihuahua and Monterrey, Mexico, in the summers of 2022 and 2023, respectively. Students are selected by CdeCMx reviewers through a competitive application process based on their STEM interests, trajectory, and motivations. Upon acceptance, they are matched to workshops aligning with their interests. Instructors are notified, and all the necessary materials and infrastructure are requested from the local institutions. All the expenses are covered by strategic partners and funds from the CdeCMx program. Workshops about different topics are held for one week at the partner institution. Additionally, sponsors and partnering institutions host professional development and networking events at the end of each day to enrich the experience.

It is worth noting that CdeCMx's approach diverges from typical academic settings; it operates more like a summer science camp than a formal university course. Students do not need to pass exams or earn grades but receive a certificate of attendance. This model focuses on sparking students' interest in STEM and exposing them to the latest scientific breakthroughs. This aspect is critical to the success of the program, and thus, workshops must be carefully designed to catch the attention of students and bring scientific innovation.

The workshop we report in this publication aims to inspire and inform young students about the critical role of electrochemical energy conversion and storage technologies in creating a sustainable future. Despite their growing importance, topics like Li-ion batteries and electrocatalysis are rarely covered thoroughly in higher education, especially in Mexican STEM programs. Our workshop leveraged the CdeCMx platform to introduce students to these critical technologies, discussing their basic principles, benefits, limitations, and pivotal role in promoting sustainability and addressing climate change.

We identified the essential concepts students needed to grasp through a backward design approach and chose engaging educational experiences to help them achieve these learning outcomes. As previously mentioned, CdeCMx's format and duration constraints do not allow for an in-depth electrochemistry course that heavily focuses on fundamentals, mathematical models, or detailed calculations. Note that this workshop is not intended to replace comprehensive courses and lectures in electrochemistry and electrochemical technologies. Instead, our goal was to introduce students to the basic operating principles of essential electrochemical technologies and their significance in society. We envision this workshop as a preliminary step to ignite interest and educate young people about the importance of these subjects. Nevertheless, we encourage the community to use our materials to expand the scope of this effort and adjust the number of topics covered, the depth of concepts, and the complexity of the activities if needed.

Lesson Plan and Topics

The workshop is structured around five key topics: electrochemistry fundamentals, water electrolysis, electrocatalysis, fuel cells, and batteries, with each topic assigned to a separate day. The daily schedule includes a mini-lecture, a hands-on demonstration or class activity (e.g., educational game), a laboratory session, and a final discussion, as outlined in the workshop timeline (**Figure 1** in the main manuscript).

The essential electrochemistry concepts are covered during the mini-lectures that introduce essential concepts through a brief slideshow. Each lecture follows a consistent format, covering the basics of operating principles, advantages, limitations, and applications to provide a concise overview of each electrochemical technology. The series begins with "*Electrochemistry Fundamentals*," progressing to more specific technologies in "*Water Electrolysis*" and "*Electrocatalysis*," which describe the kinetics and catalysis of water-splitting reactions. The sequence continues with *Fuel Cells* and concludes with *Batteries*, discussing the differences between energy conversion and storage.

It is worth noting that our pre- and post-workshop surveys reveal knowledge gaps between high school and undergraduate students, likely due to their different academic backgrounds. Although most participants lacked in-depth electrochemistry education prior to the workshop, undergraduates had some familiarity with basic concepts of thermodynamics or kinetics. Therefore, it is essential to maintain a basic level of content to suit secondary students. For example, summarizing each technology's operating principle, advantages, disadvantages, and applications gives a more general and adequate perspective for audiences of different education levels. For more advanced undergraduates, such as those studying chemical engineering, instructors could explore deeper into the operating principles and effects of conditions on each technology. Additionally, we recommend conducting preliminary assessments to understand the participants' backgrounds. This approach allows for better tailoring of the content and ensuring the workshop meets the educational needs of all the attendees.

Class Activities and Demonstrations

The activities and hands-on demonstrations complemented the mini-lectures and provided a more stimulating learning environment. Although most activities were conducted in the classroom, experiments like the Sabatier principle were conducted in a laboratory setting to ensure safety. The instructor led these activities, actively encouraging students to participate. The instructor also fostered debate among the audience, consistently questioning the reasoning behind actions and the processes occurring during the demonstrations.

Instructors are advised to prepare the testing equipment and distribute all necessary materials to students beforehand. This preparation enables students to immediately begin measurements or assemble the necessary components, ensuring experiments are conducted efficiently within the allotted time. Activities such as the mini-electrolyzer for water splitting are designed for pair work, promoting efficiency and enhancing student collaboration and interaction. Detailed explanations of each class activity and demonstration are provided in the subsequent pages of this workshop plan.

Laboratory Experiments

Experiments were crucial for introducing students to electrochemical processes and technologies discussed in the mini-lectures and demonstrations. These sessions enabled students to identify key components of electrochemical devices and assess the impact of operating conditions. They connected theoretical concepts learned in lectures with practical applications through measurements, enhancing their understanding of chemistry at the macroscopic level. Laboratory experiments also promoted systems thinking and problem-solving skills, with the instructor taking a more passive role to engage students in decision-making. Nevertheless, the instructor remained available to guide anyone as needed.

For each experiment, students worked in pairs or small groups. Following a role-playing approach, the students were assigned roles as chemists or engineers, each with specific tasks: chemists prepared solutions, conducted measurements, and analyzed data, while engineers designed, assembled, and operated the devices. Roles were rotated to diversify the learning experience and foster a dynamic, interdisciplinary environment. This role-playing approach made learning more engaging and allowed students to leverage diverse skills.

The laboratory setting provided a rich, interdisciplinary experience, exposing students to different duties, materials, and tools. For instance, in the PEM electrolyzer experiment, the "engineers" assembled the device and operated the power supply while "chemists" handled data recording and analysis. Different teams explored various catalytic materials in the electrocatalysis experiment, comparing results with other teams to deepen their understanding. In the battery experiment, students modified battery designs by adjusting electrolyte composition, electrode area, and electrode geometry. Students with expertise in electronics assisted their peers in soldering circuit boards when constructing the Arduino potentiostat. This aspect reinforced the idea that STEM education and research benefits from diverse skills and backgrounds.

The proposed experiments can be adjusted to different team sizes based on the total number of participants. However, limiting teams to four students per experiment is advisable, ensuring each member can participate actively. For semester-long courses, instructors might consider having students prepare chemicals and materials, especially if these experiments are split into multiple sessions. We encourage educators to adapt our experimental protocols to fit their educational settings and audience needs.

Class Discussions

The primary objective of class discussions was to emphasize and discuss the relevance of electrochemical energy technologies. Instead of adopting the teacher-centered approach of the mini-lectures, the instructor facilitated debates and shared pertinent information about the role of electrochemical energy conversion and storage in society. These debates and discussions raised awareness about the real sustainability of certain technologies and addressed misconceptions about how electrochemical technologies mitigate climate change. For instance, during the fourth day's class discussion on the hydrogen economy, it was revealed that not all hydrogen production technologies are truly green, a concept known as "the colors of hydrogen." Only water electrolysis powered by renewable energy is carbon-neutral, making it ideal for mitigating climate change. We provide a detailed list of additional topics and suitable references in the following pages that can be covered in each class discussion.

Although class discussions are expected to last approximately 25 minutes, instructors can extend this period if more time is available. This activity offers flexibility and versatility to instructors and provides an open space for students to share their beliefs and opinions on topics like climate change. We encourage instructors interested in adopting this approach to read the suggested references to stay informed on the sustainability, environmental impact, and economic feasibility of electrochemical energy technologies. Topics can also be tailored to specific scenarios appropriate for the workshop's scope (e.g., coupling electrolysis to solar power if the course is taught in a desert region). Overall, this space should be used to reinforce and discuss the relevance of sustainable technologies in society and global environmental health.

Final Project

The workshop's final project aimed to foster collaboration among students, apply their newly acquired knowledge and skills in a real-world context, and present their learning experiences to a broader audience. Students were tasked with presenting concepts, experiments, or experiences from the workshop during the program's closing ceremony, attended by families, friends, and other guests. Each student group from the various workshops offered at the partner institution participated in this ceremony, showcasing the diverse disciplines covered by the CdeCMx program. Students used engaging methods to ensure their presentations were attractive and comprehensible to a wide audience.

Students spent the evening of the fifth day preparing their final project with minimal assistance from the instructor, who intervened only to ensure safety if repeating a demonstration or laboratory experiment. This autonomy enabled students to plan and execute unique presentations creatively. This experience also broadened the workshop's impact beyond the classroom and inspired future participants. Partner institutions highlight this ceremony to enhance CdeCMx's visibility across various educational levels. Note that the final projects were not graded due to the program's informal setup and time constraints. However, appropriate evaluation methods could be developed by future initiatives, particularly if integrated into formal educational settings.

Day One: Introductory Electrochemistry

Objectives

By the end of this session, students will be able to:

- Describe the processes involved in electrochemical reactions.
- Identify the key components of an electrochemical cell.
- Assemble and operate a small potentiostat for electrochemical experiments.
- Construct a basic three-electrode electrochemical cell.

Instructor introduction and course overview

Allocated time: 5 minutes
Description
Use this segment to introduce yourself and concisely overview the workshop's content.

Required materials
Laptop, projector

Expected outcomes and results
None.

Notes
Highlight the requirement for students to develop a final project based on topics covered during the workshop. The final project details are outlined at the end of the workshop materials.

Class activity A1: Laboratory tour and safety protocol overview

Allocated time: 20 – 25 minutes
Description
Conduct a quick laboratory tour, emphasizing all relevant safety protocols and operational procedures. Topics include the proper use of personal protective equipment, emergency exits, emergency showers, eyewash stations, fire extinguishers, fume hood operation, and waste management practices.

Required materials
Lab coat and safety glasses (for both instructors and students).

Expected outcomes and results
Lab safety quiz (available on Quizizz.com).

Notes
Ensure students are familiar with the lab environment before beginning experiments, especially considering the varied backgrounds of the students, such as high school attendees.

Initial surveys

Allocated time: 15 – 20 minutes
Description
Conduct relevant polls or quizzes that are pertinent to the course. These are useful for tracking student understanding and progress, even if performance evaluation or demographic data collection is not a primary goal. A suggested approach involves displaying the quizzes on a large screen using a projector. The instructor leading the quiz will read out and clarify each question, managing the flow and pace of the quiz. Meanwhile, students can conveniently respond using their smartphones. Results are automatically sent to the instructor upon completion.

Required materials
Laptop, projector, smartphone.

Supporting resources
Quizzes are available at Quizzizz.com (click on the hyperlinks below).

Expectations and interests survey

Introduction to electrochemistry survey

Expected outcomes and results
Use these surveys to evaluate the workshop's effectiveness and identify areas for improvement. Additional surveys or quizzes may be implemented based on the course scope.

Notes
Quizizz.com is recommended for easy smartphone access, allowing instructors to manage the survey pace. Additional resources are available on the author's Quizizz profile: Raul A. Marquez

Lecture S1: Fundamentals of electrochemistry

Allocated time: 25 – 30 minutes
Supporting resource
Slide set: T1_Intro_Echem.pptx

Description
This brief classroom lecture will cover essential electrochemistry concepts, including chemical bonding, redox reactions, electrochemical cells, and electron transfer processes. The focus should be on conveying essential ideas (for example, identifying oxidation and reduction reactions) rather than an in-depth exploration of each topic. Grasping these foundational concepts is crucial for a deeper understanding of subsequent topics.

Required materials
Laptop, projector, laser pointer (optional).

Expected outcomes and results
Electrochemical Energy Conversion and Storage Exam (see day 5, optional)

Notes
For further preparation, consult the literature (Refs. 1,2). These topics can be expanded into longer sections, particularly if educators are willing to adapt to a different schedule, such as a semester-long course. Brief lectures are recommended, with the option to divide content into multiple sessions. We recommend consulting the work by Schmidt and colleagues,[3] which reviews some misleading analogies in electrochemistry.

Lunch break

Allocated time: 50 – 60 minutes
Description
Allocate approximately one hour for lunch, depending on the workshop schedule. This period can also serve as a buffer for adjusting other activities if necessary.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Experiment E1: Electrochemical cells and potentiostats

Allocated time: 90 – 120 minutes

Supporting resources
Handouts from Refs. 4,5.

Description
In this lab session, students will construct low-cost potentiostats as outlined in technology reports from Refs. 4,5. Students will be paired up; if possible, these pairs should collaborate throughout the workshop. This approach is designed to foster a sense of teamwork and continuity in their learning experience. To ensure the timely completion of this activity, instructors should prepare all necessary components (circuit boards, 3D-printed parts, wiring, soldering kits) in advance. Students will be responsible for soldering the electronic components, estimated to take approximately one hour.

In the subsequent hour, the instructor will install the software on each potentiostat (students need only the drivers and the executable file, not the full LabVIEW installation - see instructions in Refs. 4,5.). The instructor will then demonstrate the operation of a potentiostat using a basic electrochemical system, including a working electrode, a reference electrode, and a counter electrode. This can involve replicating one or more reactions from the references or conducting a specific experiment. Student pairs can test their potentiostats using the same electrochemical cell to verify performance consistency if time permits. Instructors should also have additional potentiostats or a commercial instrument on hand as benchmarks for testing.

Required materials
Please refer to Refs. 4,5 for materials needed to construct the low-cost potentiostat. Materials may vary based on the chosen example experiments from the references.

Expected outcomes and results
By the end of the session, each student pair will have a functioning low-cost potentiostat. These devices will be utilized in subsequent experiments (for example, Experiment E3). Instructors must ensure the software is correctly installed, and the devices are operational, as per instructions in Refs. 4,5 or by contacting this workshop's authors for additional support.

Safety considerations
Instructors must demonstrate proper soldering iron usage. Ensure students use soldering iron stands to prevent burns and wear safety glasses and lab coats at all times.

Waste management
Waste disposal procedures will depend on the electrochemical cell system used. Please follow the guidelines on Refs. 4,5 for specific reactions. Instructors should manage waste to allow students to focus on assembling and learning to operate the potentiostat.

Notes
None.

Day Two: Water Electrolysis

Objectives

By the end of this session, students will be able to:

- Describe the electrochemical water-splitting reactions.
- Identify the essential components of a water electrolyzer.
- Assemble and test the performance of a commercial water electrolyzer.
- Optimize the operating conditions of a commercial water electrolyzer.
- Contrast the advantages and limitations of water electrolysis technologies.

Lecture S2: Fundamentals of water electrolysis

Allocated time: 25 – 30 minutes
Supporting resources
Slide set: T2_Water_Electrolysis.pptx

Description
This lesson covers the essentials of water electrolysis, describing the hydrogen and oxygen evolution reactions, the concept of overpotential, the impact of electrolyte pH, and the intrinsic and extrinsic factors influencing water electrolysis efficiency. The lesson concludes with a brief description of the relevance of bubbles and ion exchange membranes.

Required materials
Laptop, projector, laser pointer (optional).

Expected outcomes and results
Electrochemical Energy Conversion and Storage Exam (see day 5, optional)

Notes
For further preparation, consult the literature (Refs. 6,7). These topics can be expanded into longer sections, particularly if adapting to a different schedule, such as a semester-long course. Brief lectures are recommended, with the option to divide content into multiple sessions.

Class activity A2: Demonstration of a mini-electrolyzer

Allocated time: 20 – 25 minutes
Supporting resources
See Ref. 8 and watch this video.

Description
This demonstration depicts the essential components of a water electrolysis system. This demonstration is detailed in Ref. 8, but we recommend adopting the design shown in this video, which is easier to construct. The experimental setup is shown in **Figure 1**. After assembling the cell and triggering the water-splitting reactions, the evolved gases accumulate inside the tubes, demonstrating water-splitting stoichiometry (2:1 for hydrogen and oxygen, respectively). Instructors can add pH indicators to highlight pH changes near electrodes, as described in Ref. 8. Depending on time and resources, this activity can be expanded to allow student pairs to construct their electrolyzers.

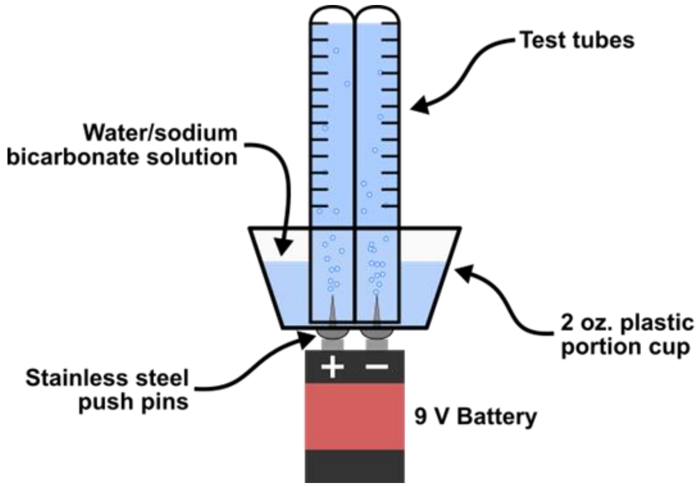

Figure 1. Schematic of the mini-electrolyzer using a 9V battery as power supply.

Required materials

This demonstration only requires a 9V alkaline battery, a plastic cup, two stainless steel pins, two plastic test tubes to collect the gases, and a mixture of water and sodium bicarbonate.

Expected outcomes and results

This demonstration is a practical and quick example of water electrolysis, prompting discussion about the reactions at each electrode and their verification through the evolved gases.

Safety considerations

Avoid using sodium chloride, as toxic chlorine gas is produced at the anode. Use stainless steel pins instead of regular steel pins to prevent corrosion at the anode. Stainless steel pins can cause puncture wounds. Instructors are encouraged to prepare all the materials in advance so that students can focus only on the water electrolysis reactions without assembling the cell.

Waste management

Dispose of the sodium bicarbonate solution in the sink. Follow local protocols for battery and sharp object disposal.

Notes

Conduct demonstrations in a tray or on an absorbent pad to manage spills (non-toxic).

Coffee break

Allocated time: 10 – 15 minutes

Description

A 15-minute break, adaptable as per the workshop schedule. Instructors should use this time for informal discussions with students, prompting additional discussion of the previous activities.

Required materials

None.

Expected outcomes and results

None.

Notes

None.

Experiment E2: Assembling and testing a commercial proton-exchange membrane electrolyzer

Allocated time: 90 – 120 minutes
Supporting resources
Student and Teacher Handouts (supporting information).

Description
This lab experiment has been specifically designed for this workshop to instruct the students on assembling and testing a commercial proton-exchange membrane (PEM) electrolyzer. Students will work in pairs, one taking on the role of an engineer to assemble the electrolyzer and the other as a chemist preparing materials and chemicals. The engineer will manage different operating conditions (temperature, current densities) while the chemist evaluates performance through electrochemical and gas evolution measurements. Throughout the class, the instructor will allocate various operating conditions. At the session's conclusion, the instructor will ask each pair about the impact of the tested conditions and their understanding of each electrolyzer component's role in observed performance. The instructor will then compile results from all groups, initiating a discussion to identify observable trends in the data and optimize the electrolyzer's performance. A detailed description of the activity, including pre- and post-lab questions, a list of materials and chemicals, and photos of the step-by-step experimental procedure are shown in the handouts.

Required materials
Please refer to the specific handouts in the supporting information. Essential components include the PEM electrolyzer, power supply, multimeter, silicone tubing, electrolyzer containers, deionized water, hot plates, 500 mL beakers, and plastic pipettes with pumps/fillers.

Expected outcomes and results
By the end of this session, each student pair will have collected a comprehensive data set from testing their PEM electrolyzer. This data set includes a cell potential versus applied current table for constructing polarization curves and a gas evolution table (hydrogen and oxygen) over 30 minutes at constant current. If laptops are available, students can plot these results using software like Microsoft Excel. The instructor may assign this as homework or incorporate it into a final project report. There is also the option for the whole class to aggregate data from all groups to analyze different temperature impacts. For more specific reporting details, refer to the handouts.

Safety considerations
The primary safety concern is handling hot water. Instructors must ensure students wear personal protective equipment (PPE), including safety glasses and lab coats. Students dealing with hot water should use heat-resistant gloves. Additionally, instructors should allocate 5 – 10 minutes to explain power supply operation and PEM electrolyzer assembly, regularly monitoring student activity for correct procedure adherence.

Waste management
Deionized water can be safely disposed of down the sink.

Notes
None.

Lunch break

Allocated time: 50 – 60 minutes
Description
Allocate approximately one hour for lunch, depending on the workshop schedule. This period can also serve as a buffer for adjusting other activities if necessary.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Class discussion: Water electrolysis research and development

Allocated time: 25 – 30 minutes
Supporting resources
Please refer to Refs. 9–13 for more in-depth concepts and ideas to guide the discussion on water electrolysis development.

Description
This session aims to engage students in discussing the significance of water electrolysis in industry, society, and climate empowerment. The instructor should shift the focus from theoretical aspects to the practical challenges in commercializing water electrolysis technologies and their potential to reduce the environmental footprint of energy and transportation technologies. Utilizing various resources like past publications or news articles, the instructor should encourage students to identify these challenges themselves, using insights gained from the water electrolysis experiments (for example, high cell potentials, the necessity for high temperatures, slow gas evolution rates, and the cost of electrolyzers).

The discussion should also cover what makes water electrolysis sustainable (non-toxic operation, safety, moderate operating temperatures, and hydrogen and oxygen as CO_2-free products). An effective approach could be to divide the class, prompting one half to identify as many advantages as possible while the other half focuses on critical challenges and limitations. After a comprehensive discussion, the instructor should highlight that while no technology is perfect, each addresses specific issues. This point is crucial and can be revisited in future discussions, such as debates on chemical fuel versus battery applications. The session should also underscore the importance of advancing sustainability and climate empowerment through water electrolysis, noting the anticipated growth of these technologies and the forthcoming need for a skilled workforce in this field.

Required materials
Whiteboard or projector (optional).

Expected outcomes and results
By the end of this session, students will have a broader understanding of the importance of water electrolysis and the challenges that need addressing to make it ubiquitous and cost-effective.

Notes
None.

Day Three: Electrocatalysis

Objectives

By the end of this session, students will be able to:

- Describe the role of catalysts in chemical reactions and their three essential properties.
- Explain the Sabatier principle for catalyst design.
- Create a Volcano plot for the hydrogen evolution reaction using different electrode materials.
- Synthesize an oxygen evolution catalyst.
- Measure the electrode overpotential through the linear sweep voltammetry technique.
- Measure the electrochemically active surface area of the catalyst using the cyclic voltammetry technique.
- Understand how catalysis research and development contribute to sustainability in industry and society.

Lecture S3: Fundamentals of electrocatalytic reactions

Allocated time: 25 – 30 minutes
Supporting resources
Slide set: T3_Electrocatalysis.pptx

Description
This lesson covers essential concepts on chemical kinetics, catalysis, and the Sabatier principle. It then explains hydrogen and oxygen evolution reactions from a catalysis perspective, detailing their mechanisms. The lecture also addresses the figures of merit for catalytic materials and various areas of catalysis research, concluding with a discussion on catalytic stability and the pre-catalytic effect observed in many electrocatalytic reactions.

Required materials
Laptop, projector, laser pointer (optional).

Expected outcomes and results
Electrochemical Energy Conversion and Storage Exam (see day 5, optional)

Notes
For further preparation, consult the literature (Refs. 14–18). These topics can be expanded into longer sections, particularly if adapting to a different schedule, such as a semester-long course. Brief lectures are recommended, with the option to divide content into multiple sessions.

Class activity A3: Constructing a volcano plot for the hydrogen evolution reaction

Allocated time: 20 – 25 minutes
Supporting resources
See Ref. 19.

Description
This demonstration illustrates the Sabatier principle and how theory and experimental electrochemistry work together. Due to time constraints, instructors are advised to prepare the materials and experiment setup beforehand (see Ref. 19 for further details) and perform the measurements in front of the students in the lab. Real-time display of measurements using a laptop and projector is recommended. Volunteers may be asked to select a material and measure the current density at a fixed potential. Students can test various electrodes or perform replicates depending on the variety of metals available. Real-time plotting of results and a discussion on the observed trends (for example, which metals strongly adsorb Hydrogen?) can follow the completion of all measurements.

Required materials
Please refer to Ref. 19 for a detailed description of the experimental setup. Essential components include a power supply, multimeter, 100 mL beakers, metal foils, salt bridge, graphite rod counter electrode, alligator clips, and 0.1 M H_2SO_4 electrolyte.

Expected outcomes and results
This experiment visually demonstrates the Sabatier principle using a representative set of electrode materials. Students will learn the significance of a Volcano plot in catalysis and identify which metals exhibit higher electrocatalytic activity for the hydrogen evolution reaction.

Notes
An alternative approach consists of using the low-cost potentiostat built by students in Experiment E1 instead of the power supply and multimeter. Each student pair can bring their potentiostat, select a metal cathode, and perform the measurement. The instructor can then compile the results into a Sabatier plot for the class, repeating the process with different teams.

Coffee break

Allocated time: 10 – 15 minutes
Description
A 15-minute break, adaptable as per the workshop schedule. Instructors should use this time for informal discussions with students, prompting additional discussion of the previous activities.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Experiment E3: Synthesizing and evaluating electrocatalysts for the oxygen evolution reaction

Allocated time: 90 – 120 minutes
Supporting resources
Student and Teacher Handouts (supporting information).

Description
This lab experiment instructs students on measuring the figures of merit of oxygen evolution reaction (OER) electrocatalysts. Students will work in pairs, one as an engineer to assemble the cells and conduct the electrochemical tests, and the other as a chemist preparing electrodes and analyzing results. The experiment includes three tasks: (1) depositing a catalytic film on Ni foam substrate via galvanostatic electrodeposition, (2) activating the catalyst using chronoamperometry, followed by linear sweep voltammetry (LSV) scans to determine the OER overpotential in 1 M KOH electrolyte, and (3) measuring the ECSA using cyclic voltammetry (CV) in nonaqueous electrolyte. The instructor will provide prepared electrolytes for each task. Three nanostructured catalysts, Ni, NiCo, and NiFe, all deposited on Ni foam substrates, will be examined. The instructor will distribute these catalysts among different teams. Students will share their results, and the instructor will discuss the materials obtained.

Required materials
Please refer to the specific handouts in the supporting information. Essential components include a 50 mL beaker, a Hg/HgO reference electrode, Ni foam substrate, Ni, Co, and Fe plating baths, potentiostats, 1 M KOH alkaline electrolyte, and 0.1 M KPF_6 electrolyte in acetonitrile (CH_3CN) solvent.

Expected outcomes and results
Each student pair will collect data, including a current versus time activation curve, a linear sweep voltammogram, and cyclic voltammograms at different scan rates. Results can be plotted using software like Microsoft Excel to determine the OER overpotential (from LSV) and ECSA (from CV). The instructor may assign this as homework or incorporate it into a final project report. The class may also aggregate data to analyze all materials collectively.

Safety considerations
The 1 M KOH electrolyte is corrosive and reacts violently with strong acids. Acetonitrile is highly flammable, toxic, and produces dangerous fumes when heated. Nickel, cobalt, and iron sulfate plating baths are toxic and environmentally hazardous. Potassium hexafluorophosphate is corrosive and potentially harmful if inhaled. All electrolytes should be prepared in advance, and students must be constantly monitored to ensure safe handling.

Waste management
Instruct students to dispose of metal plating baths, KOH, and KPF6/CH3CN electrolytes in designated containers. KOH electrolyte can be neutralized with sulfuric acid and disposed of in the sink if pH is neutralized to 7. The electrodes used should be placed in appropriate solid waste containers.

Notes
Student pairs can use their low-cost potentiostat to perform these experiments.

Lunch break

Allocated time: 50 – 60 minutes
Description
Allocate approximately one hour for lunch, depending on the workshop schedule. This period can also serve as a buffer for adjusting other activities if necessary.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Class discussion: Achieving sustainability through breakthroughs in catalysis research

Allocated time: 25 – 30 minutes
Supporting resources
Please refer to Refs. 10,16,17,20–25 for more in-depth concepts and ideas to guide the discussion on catalysis research.

Description
This session introduces students to the importance of catalysis in society and its role in achieving sustainability. The instructor can explain how catalysis reduces the energy needed for chemical reactions or replaces toxic synthesis methods with eco-friendly alternatives. The session should also address elemental sustainability and critical element recovery, discussing the high cost of noble metals and their impact on commercializing water electrolysis. To encourage critical thinking, students can brainstorm strategies to improve sustainability in catalysis based on the class activity and lab experiment results. Possible topics include reducing noble metal use, developing multimetal catalysts with synergistic effects (use the Sabatier plot to illustrate this approach), creating single-atom sites, and increasing surface area to maximize catalyst usage. The session should emphasize the critical nature of catalysis research in optimizing chemistries and enhancing the activity of non-toxic, abundant

materials for sustainability and climate change mitigation. Finally, the instructor can share experiences in electrocatalysis research and highlight the relationship between electrocatalysis and other scientific fields.

Required materials
Whiteboard or projector (optional).

Expected outcomes and results
By the end of this session, students will have a comprehensive understanding of the role of catalysis in achieving sustainability in industry and society.

Notes
None.

Day Four: Fuel Cells

Objectives

By the end of this session, students will be able to:

- Explain the differences between energy conversion and storage devices.
- Identify the main components of a typical fuel cell.
- Describe the role of hydrogen as an energy carrier in a fuel cell-electrolyzer system.
- Evaluate the impact of operating conditions on a direct ethanol fuel cell's performance.
- Determine optimal operating conditions for a direct ethanol fuel cell.
- Compare the advantages, limitations, and challenges of transitioning to a hydrogen economy.

Lecture S4: Fuel Cells Fundamentals

Allocated time: 25 – 30 minutes
Supporting resources
Slide set: T4_Fuel_Cells.pptx

Description
This lesson introduces the basics of fuel cells, starting with energy conversion principles and essential components of simple fuel cells. It then delves into factors influencing fuel cell performance, including a comprehensive discussion on irreversible losses and catalyst selection principles. The lecture further explores various types of fuel cells, their advantages, limitations, and concludes with an overview of direct liquid-fueled fuel cell technologies and their applications.

Required materials
Laptop, projector, laser pointer (optional).

Expected outcomes and results
Electrochemical Energy Conversion and Storage Exam (see day 5, optional)

Notes
For further preparation, consult the literature (Refs. 26–30). These topics can be expanded into longer sections, particularly if educators are willing to adapt them to a different schedule, such as a semester-long course. Brief lectures are recommended, with the option to divide content into multiple sessions.

Class activity A4: Circular hydrogen systems

Allocated time: 20 – 25 minutes
Supporting resources
See Refs. 17,31–33. Science kits can be found here.

Description
This activity demonstrates how hydrogen from water electrolysis can power vehicles using fuel cells. Using science kits (such as those from Horizon Educational), the instructor first explains hydrogen production in a small PEM electrolyzer. Some kits may incorporate solar panels or wind turbines to highlight renewable electricity use. Once sufficient hydrogen is produced, it fuels a cell to power a vehicle or device. Students are encouraged to operate and recharge the vehicle at the electrolyzer station. The activity also discusses the advantages of a circular hydrogen economy (Refs. 17,31–33), emphasizing CO_2-free processes and water as the only product in fuel cells. The session concludes with a discussion on the challenges and limitations of using hydrogen as an energy carrier, which will be further explored in the final class discussion.

Required materials
Two science kits are recommended: the Fuel Cell Car Science Kit and the H-Racer 2.0. One kit suffices to demonstrate circular hydrogen systems.

Expected outcomes and results
Students will visually comprehend the role of hydrogen as an energy carrier in a circular system and discuss the main advantages and limitations of using hydrogen to power vehicles.

Notes
The activity is not limited to hydrogen; biofuels can also power direct alcohol fuel cells, illustrating the similarities between sustainable and fossil fuels in terms of storage and infrastructure, with the advantages of low environmental impact.

Coffee break

Allocated time: 10 – 15 minutes
Description
A 15-minute break, adaptable as per the workshop schedule. Instructors should use this time for informal discussions with students, prompting additional discussion of the previous activities.

Required materials
None.

Expected outcomes and results
None.

Notes
None

Experiment E4: Evaluating the performance of a direct ethanol fuel cell

Allocated time: 90 – 120 minutes
Supporting resources
Student and Teacher Handouts (supporting information).

Description
This laboratory experiment, specifically designed for this workshop, educates students on evaluating and optimizing the performance of a commercial direct ethanol fuel cell (DEFC). Students will work in pairs, assuming the roles of an engineer and a chemist. The engineer is responsible for conducting measurements while the chemist prepares the ethanol compositions. Teams will test various operating conditions (temperature, ethanol concentrations) as assigned by the instructor. During the experiment, the instructor will engage each team in discussions about the impact of the tested conditions and their hypotheses regarding the observed performance. Subsequently, the instructor will gather and analyze results from all teams, stimulating a discussion to discern observable trends and optimize the DEFC's performance. The handouts detail this activity, including pre- and post-lab questions, a list of materials and chemicals, a comprehensive experimental procedure with photographs, and guidelines for presenting results.

Required materials
Please refer to the specific handouts in the supporting information. Essential components include a commercial ethanol fuel cell (options include the Bio-energy Science kit or the Ethanol Fuel Cell Science Kit from Horizon Educational), a potentiostat, a multimeter, absolute ethanol, deionized water, beakers of 100 and 500 mL, a hot plate, and plastic pipettes with pumps/fillers.

Expected outcomes and results
By the end of this session, each student pair will have collected a comprehensive data set from testing their DEFC. This data set includes an open circuit potential versus time curve and a cell potential versus delivered current table for constructing a polarization curve. If laptops are available, students can plot these results using software like Microsoft Excel. The instructor may assign this as homework or incorporate it into a final project report. There is also the option for the whole class to aggregate data from all groups to analyze different temperature and concentration impacts. For more specific reporting details, refer to the handouts.

Safety considerations
Ethanol is highly flammable and should be kept from heat, hot surfaces, sparks, open flames, and other ignition sources. It is toxic if swallowed and can cause respiratory tract irritation. Ethanol should not be disposed of down the sink.

Waste management
Instruct students to dispose of ethanol/water mixtures in designated containers, adhering to specific laboratory disposal protocols.

Notes
While the low-cost potentiostat from earlier experiments can be used, a more advanced potentiostat capable of achieving higher currents, such as the Rodeostat HC from IO Rodeo, is recommended for optimal results.

Lunch break

Allocated time: 50 – 60 minutes
Description
Allocate approximately one hour for lunch, depending on the workshop schedule. This period can also serve as a buffer for adjusting other activities if necessary.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Class discussion: The significance of the hydrogen economy in advancing climate empowerment

Allocated time: 25 – 30 minutes
Supporting resources
Please consult Refs. 10,25,31,32,34–42,42,43,43–46 for more comprehensive concepts and ideas to facilitate the discussion on the importance of the hydrogen economy.

Description
This session aims to immerse students in a conversation regarding the hydrogen economy and its crucial role in decarbonizing industry and mitigating climate change. Rather than focusing on technical details, the instructor is encouraged to discuss the pros and cons of using hydrogen as a sustainable energy carrier. Drawing from the resources mentioned above, the instructor can initiate discussions on key topics, including:

(1) The reality of climate change and the relevance of electrochemical technologies in mitigating environmental challenges.
(2) The truth about energy consumption and the need for improved energy systems.
(3) The environmental advantages of employing hydrogen to decarbonize society.
(4) Understanding the different "colors" of hydrogen and their significance.

(5) The challenges associated with hydrogen storage and transportation logistics.
(6) The advantages of hydrogen in large-scale transport (like ships and airplanes).
(7) Hydrogen's role in critical industrial sectors (such as steel manufacturing and fertilizer production).
(8) Global strategic plans for hydrogen infrastructure.
(9) The necessity of government and societal awareness in shifting towards a hydrogen economy.

After reviewing all activities up to this point, the instructor can conduct a brainstorming session, prompting students to list (using a whiteboard or projector) the benefits, limitations, and future challenges of transitioning to a hydrogen economy, considering technical, environmental, economic, and logistical factors. The instructor should remind students of all topics covered thus far (water electrolysis, electrocatalysis, fuel cells, hydrogen economy). This discussion is vital to understanding the steps required for a more sustainable society. The instructor should emphasize that current global research and development efforts target these aspects and that skilled professionals will facilitate this transition.

Required materials
Whiteboard or projector (optional).

Expected outcomes and results
By the end of this session, students will have gained a thorough understanding of hydrogen's importance as a chemical and energy carrier for achieving sustainability and addressing climate change. The brainstorming results will also assist students in recognizing the necessary steps for a transition to a more environmentally friendly society.

Notes
None.

Day Five: Batteries

Objectives

By the end of this session, students will be able to:

- Identify the main components of a typical battery.
- Describe the functioning of an ion-insertion battery.
- Illustrate the operation and characteristics of a battery using stacking tower games.
- Contrast the operating principles of ion insertion and redox batteries.
- Build an aluminum redox battery using household products.
- Determine the best strategies for improving the performance of a redox battery.
- Compare the capabilities and limitations of energy storage and conversion devices.

Lecture S5: Introduction to Battery Technology

Allocated time: 25 – 30 minutes
Supporting resources
Slide set: T5_Batteries.pptx

Description
This lesson delves into the basics of battery technology. It begins by distinguishing between energy conversion and storage, followed by an introduction to battery components, types, and performance indicators. The Li-insertion mechanism for energy storage is explored in detail, including Li-insertion energetics, compounds, ion diffusion, cathode and anode materials, and the role of the electrolyte. The lecture concludes with a discussion of the challenges facing battery technology and a brief overview of metal-air battery technology.

Required materials
Laptop, projector, laser pointer (optional).

Expected outcomes and results
Electrochemical Energy Conversion and Storage Exam (see final class discussion below)

Notes
For further preparation, consult the literature (Refs. 47–53). These topics can be expanded into longer sections, particularly if educators are willing to adapt them to a different schedule, such as a semester-long course. Brief lectures are recommended, with the option to divide content into multiple sessions.

Class activity A5: Learning battery fundamentals with stacking tower games

Allocated time: 20 – 25 minutes
Supporting resources
See Ref. 54.

Description
This activity uses a modified tower block game set to illustrate the charge and discharge processes of a Li-insertion battery, as previously reported by Driscoll and coworkers.[54] The instructor uses two tower blocks to represent the anode (graphite) and cathode (lithium-filled cobalt oxide) and demonstrates the Li-ion diffusion during charging and discharging. During the charging phase, the instructor explains how Li ions migrate out of the cobalt oxide cathode and are accommodated in the intercalation sites between graphite sheets, which increases the electrode energy. This process is demonstrated by moving Li pieces from the cathode tower to the anode tower. Next, the instructor describes the discharging process: Li ions return to the cobalt oxide cathode, their more stable state,

thereby decreasing the electrode energy. This phase involves the transfer of one electron per Li-ion moving back to the cathode. The following essential points are emphasized during this demonstration:

(1) The Li-insertion process is significantly hindered by diffusion, demonstrated by the students' speed in moving the Li pieces in and out of the towers.
(2) Completely depleting Li from the structure is not desirable, as it leads to structural instability. The instructor may engage students by asking what would occur if all lithium blocks were removed.
(3) Repeated charge and discharge cycles result in structural alterations that increasingly complicate Li insertion, leading to a more deformed tower structure and hindering the reuse of the same intercalation sites for lithium.
(4) These materials specifically store lithium due to their tailored intercalation sites. Utilizing other ions, like sodium, would necessitate materials with larger intercalation sites, meaning a larger tower block set would be required.

After elucidating these concepts, the instructor sets up additional pairs of tower blocks for student teams, each comprising around four students. The team's task is to charge and discharge their battery tower set as quickly as possible, with a challenge to maintain stability. The activity is designed to convey that the reversibility of the battery is highly dependent on the kinetics and diffusion rates of Li insertion and that rapid or repeated charging/discharging cycles lead to significant and irreversible structural changes in the battery materials.

Required materials
Modified tower blocks as described in Ref. 54. The instructors can decorate their towers differently. An example set of colors is shown in Fig. 3 in the main manuscript.

Expected outcomes and results
Students will gain an understanding of Li insertion in Li-ion batteries and how diffusion, kinetics, and structural changes affect battery performance and lifetime.

Notes
None.

Coffee break

Allocated time: 10 – 15 minutes
Description
A 15-minute break, adaptable as per the workshop schedule. Instructors should use this time for informal discussions with students, prompting additional discussion of the previous activities.

Required materials
None.

Expected outcomes and results
None.

Notes
None

Experiment E5: Building an aluminum can battery!

Allocated time: 90 – 120 minutes
Supporting resources
Please refer to handouts from Ref. 55.

Description
In this laboratory session, students will construct a redox battery using an aluminum can and bleach, adhering to the procedures detailed in Ref. 55. As in previous experiments, the students will work in pairs, assuming the roles

of an engineer and a chemist. The engineer will prepare and assemble the battery's components, while the chemist focuses on preparing the electrolyte and carrying out the measurements. Initially, the students will assemble the battery following the guidelines in Part 1 of Ref. 55. Instructors are advised to pre-cut all necessary materials to streamline the process, allowing students to focus primarily on assembling the cell and preparing the electrolyte.

Using a multimeter, each team will measure the open circuit potential (OCP) and instantaneous current density of their assembled battery. The next phase involves altering the electrolyte composition by substituting sodium hydroxide with bleach, as described in Part 2 of Ref. 55. Here, teams will again measure the OCP and current density. The final step requires students to assess the impact of the battery's design on its performance. This will involve increasing the electrode area and altering the packing geometry, as detailed in Part 3 of Ref. 55. The teams will conduct measurements of the OCP and current density after these modifications, allowing them to observe the effects of these design changes on the battery's performance.

Required materials
Please refer to Ref. 55 for a detailed description of the methods. The main materials include an aluminum can, stainless steel wool, sodium hydroxide, sodium chloride, commercial bleach, paper towels, alligator clips, a multimeter, and the low-cost potentiostat from Experiment E1.

Expected outcomes and results
Each team will create a functional aluminum redox battery and understand how different components and designs influence performance, optimizing the battery for maximum output.

Safety considerations
Handle sodium hydroxide and bleach cautiously, as they are corrosive and toxic. Avoid mixing bleach with acids to prevent toxic chlorine gas release. Be cautious of sharp can edges; instructors should pre-cut and file these to prevent injuries.

Waste management
Collect all solutions in a waste container, following lab disposal protocols. The mixture can be safely disposed of in the sink after dilution, provided commercial bleach with less than 5% NaClO is used.

Notes
None.

Lunch break

Allocated time: 50 – 60 minutes
Description
Allocate approximately one hour for lunch, depending on the workshop schedule. This period can also serve as a buffer for adjusting other activities if necessary.

Required materials
None.

Expected outcomes and results
None.

Notes
None.

Class discussion: Innovations and progress in battery technology research and development

Allocated time: 25 – 30 minutes

Supporting resources

Please consult Refs. 47,49–51,53,56–66 for more comprehensive concepts and ideas to facilitate the discussion on battery technology.

Description

This session is designed to engage students in a comprehensive discussion about the evolution and prospects of battery research and development. Battery technologies are an example of how innovation has led to practical technologies that are now integral to our daily lives. The session will highlight the development of Li-insertion technologies over the past forty years, underscoring the pivotal role of materials science and engineering in creating more stable materials with enhanced Li capacity. The discussion will then shift to the current challenges that battery research faces, which are of significant interest to companies and research institutions worldwide.

Key topics for discussion include (1) The scarcity of certain cathode metals, like cobalt, and the shift towards more abundant elements, such as iron; (2) the exploration of alternative ion-insertion approaches beyond lithium, like sodium and magnesium-ion batteries, and the challenges they present, including slower diffusion and instability; (3) the critical importance of safety in battery technology; (4) the role of battery recycling in promoting sustainability and aiding the decarbonization of society.

Furthermore, the instructor will emphasize that the technologies covered in this workshop have unique advantages and drawbacks; no single technology is the complete solution. It will be highlighted that while energy storage technologies, such as batteries, are ideal for portable devices and smaller vehicles, energy conversion technologies, like electrolyzers and fuel cells, are better suited for heavy industry, long-distance transportation, and large-scale energy generation. The session will conclude with a stress on the necessity for these technologies to work concomitantly to facilitate a genuine transition to a more sustainable society and fight climate change effectively.

Required materials

Whiteboard or projector (optional).

Expected outcomes and results

Students will gain a comprehensive understanding of the history and future challenges of battery research and development. This discussion will help students recognize the role of each sustainable technology covered in the workshop and its contribution to sustainability goals.

Notes

After this session, additional surveys and polls can be conducted. If time constraints prevent in-class completion, students can complete these as homework using Quizizz.com.

Electrochemical Energy Conversion and Storage Exam (short exam about concepts taught in this workshop)

Final Experience and Suggestions Survey

Significance of Electrochemical Technologies in Society Survey

Final Project

Allocated time: 60 – 120 minutes
Supporting resources
None.

Description
For their final project, students are encouraged to choose any topic explored during the workshop and develop a comprehensive presentation lasting 15 – 20 minutes. This culminating presentation will be part of a special event at the end of the Summer Science Camp, scheduled on Saturday. During this event, participants from all the workshops gather to showcase their activities and findings. The primary aim is to present the knowledge and skills acquired throughout the course to the audience invited to this session.

Students have the liberty to choose their preferred format for the final presentation. Possible formats include:

- Showcasing the devices built during the workshop, with live demonstrations of their functionality to the audience;
- Conducting live experiments to exhibit the principles and concepts learned;
- Designing interactive games and activities that engage the audience and facilitate participation;
- Creating and presenting digital content such as videos, music, or websites that compile all the workshop results and experiences;
- Organizing exhibitions or performances, including theater plays or other creative presentations, to convey the learned concepts.

It is crucial to remind students that the primary goal of this activity is educational: they should aim to impart knowledge to the audience. This final project also presents an opportunity to underscore the importance of the workshop topics to society, particularly focusing on sustainability, climate change, and green energy.

Required materials
The students might need a whiteboard, projector, and additional materials for their final presentation.

Expected outcomes and results
Students will create a final presentation that encapsulates one or more concepts learned during the workshop. The format of this presentation can vary widely, from a straightforward slide show to an interactive live demonstration or creative audiovisual content. This final project will serve as a gauge to determine whether the students can effectively summarize, explain, demonstrate, and connect the concepts they have learned.

Additional Notes

- Even though this workshop has been designed to minimize the use of toxic chemicals, students must wear PPE at all times. This includes gloves, safety glasses, and lab coats, with no exceptions.
- It is crucial to adhere to local waste management protocols strictly. Instructors should guide students to minimize waste generation and use designated containers for disposal. Given the workshop's emphasis on sustainability and green chemistry, educating students about the environmental impact of chemicals and promoting the twelve principles of green chemistry is vital.[67]
- To maximize the efficiency of time usage, instructors are advised to prepare all materials and chemicals beforehand. This approach allows students to concentrate on assembling, testing, and refining their electrochemical devices.
- This workshop offers flexibility for extension into longer sessions. Activities can be divided into more detailed sessions, incorporating additional concepts and ideas. Instructors should consult the individual handouts provided for specific guidelines and expanded content.

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