

Exploring green hydrogen: A case study in chemistry teaching enhanced by STEM

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Abstract: In Brazil's Northeast, Ceará stands out for its wind and solar energy production and as a key Green Hydrogen (GH₂) exporter, due to its coastal location. This study explored GH₂ as a generative theme through a STEM education approach — integrating Science, Technology, Engineering, and Mathematics — to promote interdisciplinary learning, using GH₂ as a guiding axis for articulating connections across different fields of knowledge. The methodology involved lectures, discussions, paper analysis, experiments, and surveys to evaluate students' understanding of STEM concepts and GH₂ as an alternative energy source. Students studied voltaic cells and electrolysis, assembling Daniell's cell, and producing hydrogen gas via brine electrolysis. Following these activities, students completed a questionnaire assessing their grasp of chemical concepts and their views on hydrogen production. Results indicated that students understood the interdisciplinary connections fostered by STEM and recognized the social and environmental importance of green hydrogen. The project also encouraged students to apply the knowledge they had acquired in problem-solving contexts, thereby broadening their understanding of science and its practical impact on their community and the world.

Keywords: stem education, chemistry teaching, electrochemistry.

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Resumo: No Nordeste do Brasil, o Ceará se destaca pela produção de energia eólica e solar, além de ser um importante exportador de Hidrogênio Verde (H₂V), devido à sua localização litorânea. Este estudo explorou o H₂V como tema gerador por meio de uma abordagem de educação CTEM — integrando Ciência, Tecnologia, Engenharia e Matemática — para promover a aprendizagem interdisciplinar, utilizando o H₂V como tema gerador para a articulação entre diferentes áreas do conhecimento. A metodologia incluiu palestras, discussões, análise de artigos, experimentos e questionários para avaliar a compreensão dos alunos sobre os conceitos CTEM e o H₂V como fonte alternativa de energia. Os alunos estudaram células voltaicas e eletrólise, montaram a célula de Daniell e produziram gás hidrogênio por meio da eletrólise da salmoura. Após as atividades, responderam a um questionário para verificar o entendimento dos conceitos químicos e sua percepção sobre a produção de hidrogênio. Os resultados mostraram que os alunos compreenderam as conexões interdisciplinares propostas pelo CTEM e

reconheceram a importância social e ambiental do hidrogênio verde. O trabalho também incentivou os estudantes a aplicar os conhecimentos adquiridos em contextos de resolução de problemas, ampliando assim sua compreensão da ciência e de seu impacto prático na comunidade e no mundo.

Palavras-chave: educação CTEM, ensino de química, eletroquímica.

Introduction

In the late 1990s, the National Science Foundation (NSF) in the United States was concerned about the decline in student interest and proficiency in Natural Sciences. Addressing this problem, educators, politicians, and industry leaders recognized the crucial role these disciplines play in technological progress, economic growth, and global competitiveness, leading to a series of actions focused on reformulating education to prepare students for a fast technological scenario and global challenges (Astin & Astin, 1992; Johnstone, 2000; Kuenzi, 2008; Lavi et al., 2021; National Science Foundation, 2000; National Science Foundation, 2010).

This educational movement sparked the Science, Technology, Engineering, and Mathematics (STEM) education, a term coined by the NSF in 2000. STEM's primary aim is to promote interdisciplinary learning by integrating these four areas, broadening, and linking these subjects to the contemporary challenges of society (Juškevičienė et al., 2021; Ortiz-Revilla et al., 2020).

STEM education offers more dynamic teaching, nurturing critical thinking, problem-solving, and collaboration skills among students, supporting practical application within a global context, and preparing students for job market demands (Ng, 2019; Schmidt et al., 2020; Sutaphan & Yuenyong, 2019; Wilson et al., 2014; Yang & Baldwin, 2020; York et al., 2019; Zhong, Liu, Zhan, et al., 2022). This innovative approach prepares students to become scientists and engineers by breaking down disciplinary silos and fostering research-based learning, encouraging students to apply scientific principles through hands-on projects, such as prototyping and data analysis (Baptista & Martins, 2023; Correia & Baptista, 2021; Honey et al., 2014, 2020; Lipuma et al., 2023; Pratiwi et al., 2020; Simó et al., 2020; Yang & Baldwin, 2020; Zhou et al., 2023).

Students actively investigate and solve problems using scientific principles and mathematical analysis through collaborative projects, research endeavors, or practical classes. This facilitates the connection between theoretical knowledge and its real-world applications, making abstract subjects more relevant and easier to comprehend (Baptista & Martins, 2023; Dare et al., 2021; Ghibaudi et al., 2020; Honey et al., 2014, 2020; Ivanovna & Yuriivna, 2022; Johnstone, 2000; Li et al., 2020; Lipuma et al., 2023; Ng, 2019; Shidiq et al., 2020; Sutaphan & Yuenyong, 2019).

Chemistry contents are prime candidates for STEM education. The microscopic realm of atomic and molecular structures, chemical bonds, and intangible/abstract concepts are challenging for students to grasp, particularly in making connections within the macroscopic world. Furthermore, the presence of equations, formulas, and mathematical equations adds another layer of complexity, especially for those being

introduced to the field (Ghibaudi et al., 2020; Honey et al., 2020; Lavi et al., 2021; Schmidt et al., 2020).

By leveraging the interconnected approach of STEM, educators can cultivate a stimulating and enriching learning environment, promoting a deeper understanding and appreciation of chemistry concepts. Dynamic classes are effective in incorporating experiments, software applications, and discussions about real-world applications. This hands-on approach empowers students to construct their knowledge and encourages meaningful participation in the learning process (Baptista et al., 2020; Baptista & Martins, 2023; Correia & Baptista, 2021; Ivanovna & Yuriivna, 2022; Li et al., 2020; Lipuma et al., 2023; Ng, 2019; Pratiwi et al., 2020; Shidiq et al., 2020; Simó et al., 2020; Zhou et al., 2023).

This study applies STEM education in chemistry classes focusing on electrochemistry with an emphasis on the production of Green Hydrogen (GH₂). This topic is environmentally significant and economically relevant, as evidenced by numerous discussions surrounding it in the state of Ceará, which is currently a leading producer and exporter of this energy source in Brazil (Bezerra, 2023; De Camargo et al., 2023; Forte & Gazillo, 2023; Oliveira, 2022).

Green Hydrogen (GH₂)

The production of GH₂ through water electrolysis using electricity from renewable sources such as solar, wind, or hydroelectric power, stands out as a sustainable and clean alternative. Unlike fossil fuels, GH₂ production does not emit carbon dioxide (CO₂), thereby reducing greenhouse gas emissions, the primary drivers of climate change (Du et al., 2024; Kourougianni et al., 2024; Naqvi et al., 2024).

GH₂ is essential for the global energy transition, especially in sectors that are difficult to electrify, such as heavy-duty transport, steelmaking, and chemical industries. GH₂ promotes a low-carbon economy and stimulates technological innovation, creating new markets and economic growth opportunities (Ajanovic & Haas, 2021; Bethoux, 2020; Du et al., 2024; Garlet et al., 2024; Lo Faro et al., 2023; Wallington et al., 2024; Youssef & Al-Sayed, 2024).

Moreover, the production, storage, and distribution of GH₂ generate jobs and strengthen economies, especially in countries that invest in this technology. For nations dependent on fossil fuel imports, GH₂ can represent greater energy independence and contribute to long-term energy price stability (Ajanovic & Haas, 2021; Bethoux, 2020; Du et al., 2024; Garlet et al., 2024; Lo Faro et al., 2023; Wallington et al., 2024; Youssef & Al-Sayed, 2024).

Global interest in GH₂ has attracted significant investment, leading to partnerships that develop infrastructure and technologies. Expanding this sector can generate thousands of jobs in engineering, manufacturing, and research, strengthening local communities and accelerating the transition to a sustainable economy (Garlet et al., 2024; Lo Faro et al., 2023; Schneiders et al., 2023).

Cities chosen for GH₂ production hubs typically have abundant renewable resources, robust infrastructure for production and distribution, a strong commitment to sustainability and decarbonization, a strategic location for exportation, and investments in research and innovation (Kourougianni et al., 2024).

Countries like the Netherlands, Germany, the United Arab Emirates, Canada, the United Kingdom, Australia, and Chile, are leading the way in GH₂ production. These countries excel due to their abundant natural resources, supportive sustainability policies, and unwavering commitment to decarbonization, playing pivotal roles in the global shift towards a low-carbon economy (Du et al., 2024).

Ceará, a northeastern state in Brazil with a predominantly dry and hot climate, has been chosen as a GH₂ hub due to its favorable conditions for solar and wind energy generation. The state's abundant natural resources, robust infrastructure, and supportive policies are key points in transitioning to a low-carbon economy and solidifying, globally, the state as a GH₂ producer (de Nóbrega et al., 2022; Falcão, 2023; Forte & Gazillo, 2023; Instituto de Pesquisa e Estratégia Econômica do Ceará, 2018; Naqvi et al., 2024; Pontes, 2023; Vidal, 2021).

Port of Pecém, a seaport in Ceará, serves as a key hub for exporting GH₂ to Europe, leveraging the state's strategic geographic proximity. Local policies encourage renewable energy investments, fostering a favorable environment for GH₂ production and contributing to both economic growth and job creation (Falcão, 2023; Forte & Gazillo, 2023; Garlet et al., 2024; Instituto de Pesquisa e Estratégia Econômica do Ceará, 2018; Lo Faro et al., 2023; Pontes, 2023; Schneiders et al., 2023; Vidal, 2021).

A STEM case study on electrolysis and green hydrogen (GH₂) production is a rigorous and coherent pedagogical strategy to upskill the contemporary workforce. Research in STEM education indicates that learning experiences embedded in authentic, real-world problems can enhance students' ability to apply scientific principles, engage in complex problem-solving, and develop higher-order cognitive competencies (Honey et al., 2014, 2020).

Case-based learning promotes active engagement and foster key transversal skills, including communication, creativity, collaboration, and critical thinking (Tammeleht et al., 2021). By examining the practical applications of electrolysis and sustainable energy technologies, students connect theoretical scientific knowledge with its technological and social implications, thereby deepening their conceptual understanding and strengthening their technological foresight in renewable energy and hydrogen technologies.

This study uses Green Hydrogen as a generative theme to implement experimental activities with STEM approach, and stimulating meaningful learning.

Methodology

The present study is qualitative research that seeks to understand a phenomenon through the interpretation of participants' perceptions, meanings, experiences, and narratives. This approach gives an in-depth

analysis of educational reality, prioritizing insight over numerical measurement (Levitt et al., 2021).

The specific methodology is Action Research, an approach particularly relevant for studies involving pedagogical interventions and the professional development of the educator (Cornish, F., et al., 2023).

This study followed the cyclical stages characteristic of Action Research:

- Definition of the research problem and structuring of the pedagogical intervention focusing on STEM and GH₂;
- Implementation of two lectures and experimental activities.
- Systematic data collection regarding the process and outcomes using the questionnaire and discussion circle;
- Analysis of the collected data to evaluate the effectiveness of the STEM methodology and the resulting meaningful learning.

Context and Participants

The research was conducted with 25 third-year high-school students in Fortaleza, Brazil, between April and June 2023. The primary goal was to implement and analyze STEM-based lectures on Electrochemistry. The intervention comprised two 50-minute lectures that were part of a regular Chemistry class at Presidente Medici School.

Data Collection and Analysis Instruments

Two main instruments were employed for triangulation and the deepening of results: a six-question qualitative questionnaire and a discussion circle (focus group). This questionnaire was designed to evaluate specific aspects of the pedagogical intervention.

Questions 1, 2, and 3 evaluated the comprehension of the scientific, technological, and socio-environmental aspects of GH₂, including the energetic challenges of electrolysis, the rationale for selecting Ceará as a national hub, and the potential environmental benefits associated with replacing fossil fuels. Questions 4 and 5 focused on the pedagogical approach, identifying differences between the STEM-based and traditional lessons, and the students' ability to recognize the interdisciplinarity. Question 6 examined meaningful learning and knowledge transfer to real-world contexts.

After the questionnaire, a discussion circle was conducted, functioning as a focus group. This expanded and deepened the students' perceptions, promoting critical dialogue about STEM education. The textual data gathered from the questionnaire and the transcripts of the discussion circle were analyzed using content analysis (Öndeş, 2025). The analysis comprised of pre-analysis, material exploration, and treatment of results, enabling the categorization and interpretation of units of meaning related to student engagement, motivation, and comprehension of scientific concepts.

The first lecture focused on context, foundation, and baseline assessment, divided into:

a) discussion of STEM education principles and relevance, assessing students' prior knowledge in electrolysis, GH_2 , H_2 -powered vehicles (H_2V), and potential applications in their hometown.

b) guided analysis of the article, "Primeira molécula de Hidrogênio Verde produzida no Brasil é lançada no Ceará" (Ceara.gov, 2023). Students read the article and reflected on the global, national, regional, and local relevance of GH_2 discussing its potential pros and cons, including the scientific and technological aspects of production and commercialization.

c) discussions that extended to H_2V , exploring ZeroAvia's work in H_2 -powered aircraft. Students were introduced to the Hindenburg disaster (1937) caused by a catastrophic H_2 gas leak. This accident highlighted the inherent danger of H_2 -air mixtures, raising a profound question: Can scientific advances eliminate the risk of accidents of this kind?

d) deepening into electrolysis, spontaneous reactions, electrolytic processes, metal oxidation–reduction reactions, alternative methods for H_2 production, potential difference, and the relationship between work and energy.

The second lecture was structured around three core phases: a hands-on electrochemical demonstration, data collection, and a discussion circle. The class was divided into groups of six students. Under supervision, each group conducted two practical electrochemical experiments.

The first experiment was the electrolysis of a saturated sodium chloride solution (brine) using alternative materials (PET bottle, pencil graphite, and 1.5 V batteries), shown in Figure 1a. Visual confirmation of H_2 gas production was confirmed by inflation of a rubber balloon. Phenolphthalein was used to confirm the formation of hydroxyl ions (OH^-).

The second experiment was Daniell cell (Figure 1b) assembly to demonstrate a spontaneous redox reaction, using zinc (Zn) and copper (Cu) electrodes immersed in ZnSO_4 and CuSO_4 solutions, respectively. The potential difference (p.d.) was measured and compared to the theoretical value.

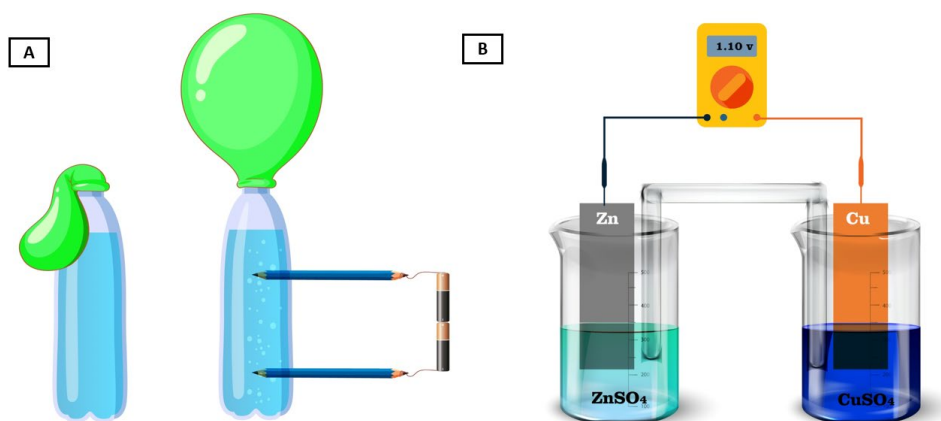


Figure 1.- Scheme of Experiments: (A) hydrogen gas release (B) Daniell's cell.

Following the experiments, the conceptual difference between spontaneous and non-spontaneous (electrolysis) reactions was reinforced using Gibbs free energy and Nernst potential (Table 1).

Experiment	Electrode	Semi-reaction	Nernst Potential (V)	ΔG_{298}^0 (KJ/mol)
Electrolysis	Anode (+)	$2Cl^-(aq) \rightleftharpoons Cl_2(g) + 2e^-$	+1,36	+262,4
	Cathode (-)	$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	-0,83	+159,8
	Overall reaction	$2Cl^-(aq) + 2H_2O(l) \rightleftharpoons Cl_2(g) + H_2(g) + 2OH^-(aq)$	+2,19	+422,2
Daniell cell	Anode (-)	$Zn^0(s) \rightleftharpoons Zn^{2+}(aq) + 2e^-$	-0.76	-889
	Cathode (+)	$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu^0(s)$	+0.34	-676
	Overall reaction	$Zn^0(s) + Cu^{2+}(aq) \rightleftharpoons Zn^{2+}(aq) + Cu^0(s)$	+1.10	-1,565

Table 1.- Semi-reactions, Nernst potential and Gibbs free energy of the brine electrolysis and Daniell cell.

After completing the experimental activities, the students answered a qualitative questionnaire with six open-ended questions. This instrument was designed to evaluate specific aspects of the pedagogical intervention, with the following distribution and rationale: Questions 1, 2, and 3 assessed the understanding of the scientific, technological, and socio-environmental aspects of GH₂, including energy challenges, the relevance of Ceará as a national hub, and the potential environmental benefits of replacing fossil fuels. Questions 4 and 5 focused on evaluating the pedagogical approach, identifying the differences between STEM-based classes and traditional classes, and the students' ability to recognize the interdisciplinarity. Question 6 examined meaningful learning and the transfer of knowledge to real-world contexts.

Following the questionnaire, a discussion circle was conducted, operating as a focus group. The objective was to expand and deepen the students' perceptions, promoting critical dialogue about the relevance of STEM education and its applications. The narratives collected in this instrument complemented the written responses.

The textual data obtained from the questionnaire and transcripts of the discussion circle were subjected to the content analysis technique. The analysis followed the phases of pre-analysis, exploration of the material, and treatment of the results, allowing for the categorization and interpretation of the units of meaning related to engagement, motivation, and understanding of scientific concepts.

Results and discussion

STEM has become a global educational approach that fosters interdisciplinary learning to solve real-world problems, exposing students to diverse perspectives, and promoting a nuanced comprehension of complex issues.

Scientific, technological, and investigative reasoning were encouraged from the beginning, with informal discussions, case studies of news articles, and hands-on experiments. Our mission was to instill a comprehensive skill set in students, empowering them to investigate, discover, connect, communicate, create, and reflect. The evidence of learning was identified through systematic observation of students' participation during the reading and analysis of the news article on GH_2 . Throughout these interactions, students were able to recognize advantages and limitations, socio-environmental impacts, and concrete technological applications, such as transportation systems and sustainable energy production.

These observations indicate that the students not only assimilated the central concepts but also applied them critically, demonstrating the potential of the STEM approach to promote meaningful and socially relevant learning.

Experimentation

Based on the systematic observation and active participation of the students during the experimental activities, it was possible to identify clear evidence of both conceptual and procedural learning. The students demonstrated comprehension that the graphite electrodes should not come into direct contact to avoid an immediate flow of electric current, that could cause an explosion in the presence of H_2 —an insight that emerged from their own analyses and

The students constructed their own devices for H_2 production via electrolysis of brine solution, developing competencies, such as peer collaboration, argumentative ability, scientific communication, spontaneous leadership, hypothesis formulation, creativity, and critical thinking in interpreting the phenomena observed.

The progressive autonomy in handling the materials and explaining the results indicates that the students were able to transfer and apply previous scientific knowledge to a new experimental context. This behavior is a robust indicator of significant learning and cognitive engagement.

Experimentation in chemistry education serves as a cornerstone to nurture meaningful learning, providing students with hands-on, tangible experiences that transcend the confines of theoretical knowledge. Tactile engagement helps students grasp abstract concepts more deeply. It also incentivizes active participation by cultivating essential skills, including curiosity, critical thinking, and problem-solving. (Dunn et al., 2012; Martín-Páez et al., 2019; Sudarmin et al., 2023; Zhong, Liu, Xia, et al., 2022; Zhong, Liu, Zhan, et al., 2022).

Experimentation also stimulates the development of crucial interpersonal skills, including teamwork, communication, responsibility, problem-solving aptitude, and motivation. This holistic and interactive approach, which seamlessly blends theoretical knowledge with practical hands-on experience, cultivates a deeper comprehension and appreciation among students (Martín-

Páez et al., 2019; Sudarmin et al., 2023; Zhong, Liu, Xia, et al., 2022; Zhong, Liu, Zhan, et al., 2022).

Qualitative evaluation

The first question made students reflect on solutions for GH₂ generation, seeking alternatives for the use of renewable sources for its production, contributing to solving the challenge of energy demand.

It is not a question of finding a solution, but rather putting it in the balance, Green Hydrogen via electrolysis is a path to a world with less carbon emissions, in addition to being useful in many areas of human life, in other words, the solution is investment for a better future. (Student 01)

Investment in solar energy, which by the way in the Pecém complex, where the implementation of the Hydrogen Green unit in Ceará is being carried out, already has solar energy plants, and could be an option for reducing costs and the amount of energy for generation of Green Hydrogen. (Student 02)

Student 01 comprehended the harmful effects of polluting gases on the environment and recognized the versatile potential of GH₂. Student 02 demonstrated prior knowledge of GH₂ production facilities in Ceará, suggesting a connection to their local environment or media exposure.

Students were tasked to describe the reasons why Ceará was chosen as a GH₂ hub in Brazil (Question 02). Many cited the geographical location and seaports, as well as the climate and the historical propensity to produce renewable energy, as can be seen below.

Strategic issues such as suitable climate for the activity, and geographical position, since Ceará is a state with an extensive coastline, which facilitates international relations. (Student 03)

Abundant sources of renewable energy such as wind and solar and as producing Green Hydrogen through electrolysis requires an energy source, these can be good alternatives that helped to choose Ceará. (Student 04)

I believe it is due to its ability to produce clean energy and its location in the Atlantic Ocean. (Student 05)

Due to its great potential for solar and wind energy, which can be used in the production of Green Hydrogen. (Student 06)

Because the state is a reference in the production of renewable energy, and because it has seaports that facilitate trade abroad, it is the perfect territory for production. (Student 07)

The students related GH₂ production to local geography, energy production, and commodification, indicating an interdisciplinarity in their answers. Madden and Asghar mention that the STEM approaches students with several concepts concurrently (Asghar et al., 2012; Madden et al., 2013).

The participants recognized the benefits of GH₂ (Question 3) to minimize the environmental impact when compared to fossil fuels that release toxic gases into the air.

As the use of Green Hydrogen becomes more popular, there will be a reduction in the use of fossil fuels and thus a reduction in the emission of polluting gases such as carbon dioxide, which will benefit the environment. (Student 08)

I believe so since it consists of energy that is made up of renewable sources, inexhaustible and non-polluting. (Student 09)

Yes, it is 100% sustainable, does not emit polluting gases during combustion or production processes, and does not negatively affect the environment with gases that cause the greenhouse effect. (Student 10)

Yes, since several countries are dependent on fuels imported from other countries, this investment is a good opportunity for Brazil, and the environment is also grateful because the production process is clean and its use does not generate polluting gases. (Student 11)

It is a very advantageous production, considering its sustainability, the fact that it does not emit polluting gases during its combustion does not harm the environment. (Student 12)

The differences observed by the students about STEM education were also investigated (Question 4). The results pointed to a positive assessment, especially regarding experimentation, interdisciplinarity in discussions, and the frequent relationship with everyday life.

The practical activities streamlined theoretical teaching and made connections with our daily lives, facilitating the relationship between disciplines and leaving everything with a revolutionary and innovative aspect. (Student 13)

I found it different and necessary since most classes in this subject only see theory without practice, it's cool to see the application of things. (Student 14)

Yes, I felt more immersed in the class, I understood the explanation better, mainly because of the experiment that linked theory to practice. (Student 15)

It was great to get away from theory, see applications within our reality, and realize that the disciplines are interconnected. Besides, I was out of touch with current issues that are important for our future as Green Hydrogen. (Student 16)

Changing the methodology of classes from time to time is great! I felt more excited, with this more dynamic, more participatory class, interesting mainly for the experiments and for realizing that Sciences are interconnected, something I had never noticed before. (Student 17)

Yes, through this methodology I was able to see that Chemistry is also present in other subjects and different areas of activity beyond our daily lives. (Student 18)

Yes, I really liked this methodology because it works on current and relevant topics in our society, different from what we see every day at school, in addition to showing it in practice, this involves students more and sees that Chemistry is 'in' Biology, Physics, in Mathematics, Engineering, and Technological products. (Student 19)

Interdisciplinarity and contextualization constitute two complementary curriculum principles that contribute to perception of reality as a complex system. STEM stimulates the organization and interconnection of knowledge bridging theoretical knowledge and practical applications (Asghar et al., 2012; Correia & Baptista, 2021; Dare et al., 2021; Kelley & Knowles, 2016; Madden et al., 2013; Yang & Baldwin, 2020).

Students were tasked to cite examples of electrochemistry applications in their routine using STEM method (Question 06). All answers pointed out at least one example of this relationship:

I notice when I use devices that require batteries, for example, remote controls, calculators, watches, and devices such as cell phones and notebooks. (Student 20)

Electric gates, toys that have batteries. (Student 21)

Cell phones, television, car batteries. (Student 22)

In the last classes, I realized how Chemistry is present in everything in our daily lives. I can see electrochemistry in remote controls, toys, watches, cars, anything that has batteries to make it work. (Student 23)

The debate circle about STEM and GH₂ generation, pointed to experimentation as the main driver of STEM methodology acceptance.

I liked the methodology, mainly because I never had the opportunity to put the theoretical part into practice, and this motivated me to research because I like seeing these things, I am fascinated by these experiments. (Student 24)

I paid attention in the last class. The content was interesting, I'm not going to lie, it was much more interesting than the other classes, right? I'm much more willing to understand chemistry more and this was a good class. (Student 25)

STEM methodology was well-received in class not only for motivating students but also for serving as a tool for Chemistry teaching.

Although the study was conducted in a specific educational context, which limits broad generalizations and the assessment of long-term effects, its results offer relevant contributions to the discussion of innovative pedagogical practices in chemistry education. By assuming an exploratory and contextual character, the research provides meaningful insights into the potential of integrating STEM education, case studies, and experimentation as strategies to promote student engagement and meaningful learning. In this sense, the findings contribute to the literature in science education by illustrating how interdisciplinary and contextualized approaches can support chemistry teaching in real classroom settings.

The findings highlight important pedagogical impacts for the school community, demonstrating that the articulation between contemporary socio-

scientific issues, such as green hydrogen, and interdisciplinary approaches can enhance student engagement, support the contextualization of abstract chemical concepts, and foster the development of essential competencies, including critical thinking, collaboration, and problem-solving. In this way, the study reinforces the role of chemistry education as a formative agent in addressing current social, environmental, and technological challenges, while also providing theoretical and methodological contributions to future research and educational practices aligned with sustainability and STEM education.

Conclusion

Students achieved significant results when stimulated through STEM education. The case study on GH_2 production, promoted discussions, experimentation, and reflections, enabling students to develop effective problem-solving skills. The teacher played a crucial role in guiding the process, helping to build investigative paths, and leading students to comprehend both the risks and the technological advancements.

The lecture connected GH_2 with students' daily lives, promoting significant learning. Experimentation made students develop interpersonal, communication, and leadership skills, and apply scientific knowledge by comparing theoretical values to practical measurements, understanding the spontaneity of electrochemical processes.

The questionnaire results revealed a successful outcome in engaging and motivating students with STEM. The participants were highly receptive and enthusiastic about the opportunity to conduct independent research on a theme relevant to their daily lives. Experimentation proved essential, facilitating learning in a playful yet motivating manner. By empowering students to act as protagonists in constructing their knowledge, this strategy fostered greater interest and proved to be an effective educational approach.

The exploration of GH_2 was a successful case study that aligned with STEM education goals. This integrated methodology proved to be a highly effective catalyst for sparking student interest, engagement, and deep, multidimensional understanding. The result was an enriching educational experience that promoted meaningful learning and the construction of a solid knowledge base.

Future research may deepen and expand this investigation by addressing different educational levels, enabling a more comprehensive analysis of the impact of the proposed approach. Systematic comparisons of learning outcomes between STEM-based strategies and traditional teaching methodologies can contribute to strengthening the evidence obtained. Furthermore, subsequent studies may explore the incorporation of other themes related to sustainable energy, as well as the use of advanced technological tools, such as digital simulations and data analysis software, in order to further enhance the interdisciplinary and innovative nature of STEM education in chemistry teaching.

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