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Analysis of Students' Argumentation Skills in Socioscientific Issue-Based Electrochemistry Learning on Electric Vehicle Batteries

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Abstract

Scientific argumentation is essential for enabling students to evaluate evidence and make informed decisions about complex scientific and technological issues. This study aimed to describe chemistry education students' argumentation skills in socioscientific issue-based electrochemistry learning using electric vehicle batteries as the context. A descriptive study using qualitative content analysis supported by descriptive statistics was employed. The participants were 15 undergraduate chemistry education students selected through total sampling. Data were collected through a five-item written argumentation test and semi-structured interviews with six students representing high, moderate, and low performance categories. Students' responses were analyzed using Toulmin's argumentation components: claim, data, warrant, backing, qualifier, and rebuttal. The results showed that students' overall argumentation skills were at a moderate level. Five students (33.3%) were classified in the high category, seven (46.7%) in the moderate category, and three (20.0%) in the low category. Claim was the strongest component, whereas rebuttal was the weakest. High-performing students were able to connect electrochemical concepts with battery production, degradation, recycling, and environmental impacts, while lower-performing students relied more heavily on general opinions and showed limited scientific justification. These findings indicate that socioscientific issue-based electrochemistry learning should provide more explicit support for developing warrants, qualifiers, and rebuttals.

Keywords: Argumentation skills; socioscientific issues; electrochemistry; electric vehicle batteries; Toulmin argumentation pattern

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INTRODUCTION

Scientific argumentation is a central practice through which learners justify claims, evaluate evidence, connect observations with disciplinary principles, and respond to alternative explanations. In chemistry education, this practice is particularly important because meaningful understanding requires students to move beyond recalling definitions or applying algorithms and to use chemical knowledge in explaining and judging real phenomena. Electrochemistry provides a productive yet demanding setting for this purpose. Students must coordinate oxidation–reduction processes, anode and cathode functions, electron and ion movement, cell potential, battery performance, and material degradation while shifting among macroscopic, particulate, and symbolic representations. These concepts are directly connected to contemporary energy technologies, particularly lithium-ion batteries used in electric vehicles. Consequently, electrochemistry learning should not be isolated from the technological, environmental, and social systems in which batteries are produced, used, and discarded. Contemporary chemistry education therefore increasingly emphasizes evidence-based practice and systems-oriented learning that helps students relate chemical mechanisms to broader sustainability problems (Cooper & Stowe, 2018; York et al., 2019). Socioscientific issues (SSI) offer an appropriate pedagogical context because they are authentic, complex, and open-ended problems whose resolution requires scientific evidence as well as consideration of social values and competing interests. Engagement with SSI can support functional scientific literacy by requiring learners to investigate information, consider multiple perspectives, formulate defensible positions, and participate in reasoned discourse (Zeidler et al., 2019). Recent empirical studies also show that explicitly scaffolded SSI-based learning can strengthen the complexity, evidential quality, and responsiveness of students' scientific arguments (Aziz & Johari, 2023; Dawson, 2024, 2025; Karaman Türk & Çam, 2025).

The sustainability of electric vehicles illustrates why such contextualized reasoning is urgently needed. Electric vehicles can reduce direct exhaust emissions during operation, but their overall environmental performance cannot be judged solely at the point of use. Life-cycle studies show that battery capacity, electricity sources, manufacturing energy, material composition, vehicle lifetime, and recycling pathways influence environmental outcomes (Ellingsen et al., 2016; Peiseler et al., 2024). Moreover, lithium-ion battery production depends on critical materials such as lithium, cobalt, nickel, and manganese, while the type of battery chemistry influences material demand and vulnerability across the supply chain (Cheng et al., 2024; Wang et al., 2023; Xu et al., 2020). At end of life, spent batteries create both hazards and opportunities. Improper handling may contribute to fire, explosion, and contamination risks, whereas effective collection, reuse, and recycling can recover valuable materials and reduce demand for primary resources (Jiang et al., 2025; Ma et al., 2024; Mrozik et al., 2021). Recycling technologies also differ in energy requirements, greenhouse-gas emissions, material recovery, and economic feasibility (Ciez & Whitacre, 2019). These tensions make electric-vehicle batteries a genuine SSI rather than a problem with one technically correct answer. Students must weigh benefits against limitations, distinguish evidence from opinion, connect electrochemical principles with environmental consequences, and qualify conclusions according to relevant conditions. Such competencies are important for chemistry students who will later teach, communicate, or make decisions about emerging technologies. Research on SSI has shown that well-designed learning experiences can foster socioscientific reasoning, including attention to complexity, inquiry, skepticism, and perspective taking (Romine et al., 2017; Zeidler et al., 2019).

Despite the educational potential of SSI, important gaps remain. Studies have demonstrated that sustained engagement with environmental SSI can improve socioscientific reasoning and environmental literacy, and research has developed validated measures for assessing students' reasoning about complex issues (Kinslow et al., 2019; Romine et al., 2017). Other work has shown that argumentation is strengthened when learners coordinate claims with evidence, scientific justification, and multiple representations rather than merely state a preferred position (Namdar & Shen, 2016). Previous studies have also shown that learners may differ in their ability to evaluate argument persuasiveness, coordinate evidence with claims, and construct counterarguments and rebuttals in socioscientific contexts (Archila et al., 2023;

Çapkınoğlu et al., 2020, 2021; Dawson & Venville, 2022). Nevertheless, comparatively limited attention has been given to how university chemistry students construct complete arguments when an SSI requires them to integrate electrochemical concepts with the environmental and social dimensions of battery technology. Existing research often evaluates broad outcomes or overall socioscientific reasoning; consequently, less is known about the relative quality of individual argumentative components. This distinction is important because a student may express a clear claim while providing weak data, an incomplete warrant, limited theoretical backing, no qualification, or no response to counterarguments. The present study addresses this gap by examining six interrelated components—claim, data, warrant, backing, qualifier, and rebuttal—in the context of electric-vehicle batteries. Its novelty lies in combining a discipline-specific electrochemistry context with an authentic sustainability controversy and examining both the structural completeness and scientific substance of students' arguments. Written responses are complemented by interviews with students representing different performance categories, allowing the analysis to explore how students explain their reasoning, connect chemistry with environmental concerns, and respond to opposing viewpoints.

Accordingly, this study aims to describe and analyze the argumentation abilities of chemistry education students after participating in SSI-based electrochemistry learning focused on electric-vehicle batteries. Specifically, it seeks to determine the overall distribution of students' argumentation performance; examine the quality of claims, data, warrants, backing, qualifiers, and rebuttals; identify the strongest and weakest components; and explain how students connect electrochemical knowledge with issues of mineral extraction, battery operation and degradation, safety, waste management, and recycling. The study is bounded to 15 students in a chemistry education program who had completed electrochemistry instruction and participated in learning activities organized around the question of whether electric-vehicle use should continue to expand while battery production and disposal still create environmental challenges. Argumentation is examined through written SSI tasks and selected interviews, with quantitative scores used to summarize component-level patterns and qualitative analysis used to interpret the reasoning expressed in students' answers. The study does not test the causal effectiveness of SSI instruction against a comparison group; rather, it develops an empirical profile of students' argumentation after the learning experience. By locating conceptual understanding within a socially consequential technological issue, the study is expected to clarify whether students can progress from simple expressions of agreement or disagreement toward scientifically supported, qualified, and responsive arguments. The findings may inform the design of electrochemistry instruction, argumentation rubrics, and future SSI activities intended to strengthen evidence-based decision making in university chemistry education.

METHOD

Research Design

This study employed a descriptive study using qualitative content analysis supported by descriptive statistics. The qualitative component was used to examine the structure, scientific substance, and reasoning patterns evident in students' written and oral arguments. The quantitative component was used to summarize the distribution of argumentation levels and the achievement of each argument component. This design was selected because the study was intended to develop an empirical profile of students' argumentation rather than determine the causal effectiveness of an instructional treatment. Accordingly, the study did not employ a control group, random assignment, or pretest–posttest comparison.

The unit of analysis was the individual argument produced by each student after participation in socioscientific issue-based electrochemistry learning. The learning context focused on electric-vehicle batteries and the central question of whether electric-vehicle use should continue to expand despite environmental, safety, material-extraction, and end-of-life battery concerns. Students were required to evaluate the issue by integrating electrochemical concepts with relevant technological and environmental considerations.

The learning activities consisted of five sequential stages: issue orientation, reinforcement of electrochemical concepts, analysis of evidence, individual argument construction, and discussion and reflection. During issue orientation, students were introduced to competing perspectives on electric vehicles and lithium-ion batteries. They subsequently reviewed relevant concepts, including redox reactions, anodes and cathodes, electron and ion movement, battery degradation, and recycling. Students then examined evidence supporting different positions, constructed individual arguments, and discussed alternative viewpoints before completing the research task.

Participants and Research Context

The participants were 15 undergraduate students enrolled in the Chemistry Education Study Program at Universitas Pendidikan Mandalika, Indonesia. All participants had completed the electrochemistry unit when the study was conducted. Because the study involved all students in one intact class who met the participation criteria, total sampling was used. The inclusion criteria were enrollment in the relevant electrochemistry course, participation in the SSI-based learning activities, and completion of the written argumentation test. The analysis did not use demographic characteristics as comparison variables because the research focused on the quality and structure of the arguments produced.

To protect participant identities, each student was assigned an anonymous code ranging from M01 to M15. All 15 students were included in the quantitative summary and written-response analysis. Following the scoring and categorization of the written arguments, six students were selected purposively for semi-structured interviews. The interview participants represented variation in argumentation performance and consisted of two students from the high category, two from the moderate category, and two from the low category. The selected participants were M03 and M12 from the high category, M02 and M10 from the moderate category, and M04 and M11 from the low category.

This maximum-variation selection was intended to reveal differences in how students with different performance levels used evidence, applied electrochemical concepts, qualified their positions, and responded to opposing arguments. The interview sample was therefore not intended to provide statistical representation but to support a more detailed interpretation of the written-test patterns.

Research Instruments and Data Collection

Two principal instruments were used: a written SSI-based argumentation test and a semi-structured interview guide. The written test consisted of five open-ended questions related to the use, production, safety, environmental consequences, and recycling of electric-vehicle batteries. The questions required students to state a position, provide relevant evidence, explain the scientific relationship between the evidence and their position, apply electrochemical concepts, identify limitations or conditions, and respond to potential counterarguments.

Students' responses were assessed using an analytic rubric based on six argumentation components: claim, data, warrant, backing, qualifier, and rebuttal. The operational definitions are presented in Table 1. The rubric was developed with reference to applications of Toulmin's Argument Pattern in science education, in which the quality and complexity of arguments are examined through the relationships among claims, data, warrants, backing, qualifiers, and rebuttals (Erduran et al., 2004).

Table 1. Operational indicators of students' argumentation

Component	Operational indicator
Claim	A clear and relevant position concerning the SSI
Data	Facts, information, observations, or scientific concepts supporting the claim
Warrant	Scientific reasoning explaining how the data support the claim
Backing	Additional theories or electrochemical principles strengthening the warrant
Qualifier	Conditions, limitations, or degrees of certainty attached to the claim
Rebuttal	Recognition and reasoned response to an alternative or opposing position

Each component was scored from 0 to 3 for each question. A score of 0 indicated that the component was absent or irrelevant; 1 indicated that it was present but unclear, scientifically weak, or insufficiently developed; 2 indicated that it was relevant and generally accurate but only partially elaborated; and 3 indicated that it was clear, scientifically appropriate, and well integrated into the argument. Because the test contained five questions, the maximum score for each component was 15, and the maximum overall argumentation score was 90.

Content validity was addressed by aligning the test questions and scoring rubric with the research objectives, electrochemistry content, the electric-vehicle battery issue, and the six argumentation indicators. The instrument review focused on conceptual accuracy, relevance to the SSI context, clarity of language, and correspondence between each question and the intended argument component.

After the written responses had been scored, semi-structured interviews were conducted with the six selected students. The interviews consisted of four principal questions concerning the students' positions on electric vehicles, evidence used to support those positions, connections between the issue and electrochemical concepts, and responses to opposing perspectives. Follow-up questions were used when clarification was required. The interviews also explored difficulties in producing scientific reasons and rebuttals. Responses were transcribed and organized according to participant code.

Data Analysis

Quantitative and qualitative analyses were conducted sequentially and then integrated during interpretation. First, each student's written response was scored using the six-component rubric. The five item scores for each component were summed, producing a maximum component score of 15. The six component scores were subsequently summed to obtain an overall score with a maximum of 90. Each student's percentage score was calculated using the following formula:

$$\text{Argumentation percentage} = \frac{\text{Obtained score}}{90} \times 100$$

Students were classified into three performance categories: high for scores of 76–100%, moderate for scores of 56–75%, and low for scores of 55% or below. The mean score for each argument component was also calculated and divided by the maximum component score of 15 to determine its percentage achievement. These descriptive results were used to identify the overall performance tendency and the relatively strongest and weakest components.

Second, qualitative content analysis was applied to the written responses and interview transcripts. The analysis involved reading the complete dataset, identifying meaningful argument units, assigning deductive codes corresponding to claim, data, warrant, backing, qualifier, and rebuttal, and comparing the resulting patterns across the high, moderate, and low categories. Additional descriptive codes were applied to statements indicating conceptual difficulty, reflective awareness, reliance on general opinion, and difficulty responding to opposing viewpoints. These additional codes were used for interpretation but were not included in the numerical argumentation score.

Written and interview findings were compared to determine whether the explanations provided during interviews confirmed, expanded, or contradicted the patterns found in the written responses. For example, a weak written rebuttal was examined alongside the participant's explanation of the difficulty experienced when responding to an opposing position. This integration allowed the numerical profile to be interpreted using students' own reasoning.

To improve the dependability and transparency of the coding process, coding definitions, decision rules, and representative examples were documented. A second-rater review and consensus discussion were used to examine ambiguous segments and refine coding decisions. Independent checking and discussion of disagreements are recognized as useful procedures for improving the systematicity and transparency of qualitative coding (O'Connor & Joffe, 2020).

RESULTS AND DISCUSSION

Overall Profile of Students' Argumentation Skills

The analysis of the written argumentation test showed substantial variation in students' ability to construct scientific arguments concerning electric-vehicle batteries. The total scores ranged from 40 to 79 out of a maximum score of 90. The mean total score was 60.93 (*SD* = 12.26), equivalent to 67.70%, indicating that the overall argumentation skills of the participants was in the moderate category. Five students (33.3%) were classified in the high category, seven students (46.7%) in the moderate category, and three students (20.0%) in the low category. Thus, almost half of the participants could construct arguments containing several relevant components, although their arguments were not consistently complete or sufficiently elaborated. The distribution also indicates that students' ability did not form a homogeneous pattern. Some students could integrate scientific concepts, environmental evidence, and alternative perspectives, whereas others relied primarily on general opinions concerning the perceived advantages of electric vehicles. The individual scores further demonstrate this variation: the highest scores were obtained by M03 and M12, with 79 and 78 points, respectively, while M11 obtained the lowest score of 40 points. These differences provided the basis for comparing the qualitative characteristics of arguments across the three performance categories.

Table 2. Distribution of students' argumentation skills

Category	Score criterion	Number of students	Percentage
High	76–100%	5	33.3%
Moderate	56–75%	7	46.7%
Low	≤55%	3	20.0%
Total		15	100.0%

The predominance of the moderate category suggests that most students had begun to move beyond unsupported opinion but had not yet developed consistently sophisticated scientific arguments. They were generally able to select a position and provide basic information about emissions, battery waste, redox reactions, or electron transfer. However, they did not always explain why the information supported their position or how the benefits and risks of electric vehicles should be weighed against one another. This finding is consistent with the distinction between possessing relevant scientific information and using that information epistemically to justify a conclusion. Scientific argumentation requires students not only to possess relevant scientific information but also to coordinate claims, evidence, scientific reasoning, and alternative perspectives when evaluating complex issues (Namdar & Shen, 2016; Romine et al., 2017). In the present study, the electric-vehicle battery issue created opportunities for such reasoning because it could not be resolved through a single factual statement. Students had to consider battery operation, electricity sources, mineral extraction, environmental impacts, safety, and recycling simultaneously. Socioscientific reasoning similarly involves recognizing complexity, examining evidence critically, and considering multiple perspectives rather than selecting a position solely from personal preference (Romine et al., 2017; Zeidler et al., 2019). Nevertheless, because the study did not employ a pretest or comparison group, the distribution should be interpreted as a descriptive profile after SSI-based learning rather than evidence of a causal instructional effect.

Quality of the Six Argumentation Components

The component-level analysis revealed a gradual decline from the basic components of argumentation to the more complex components. Claim was the strongest component, with a mean score of 11.87 out of 15, equivalent to 79.1%. It was followed by data at 11.20 (74.7%), warrant at 10.67 (71.1%), and backing at 9.93 (66.2%). Qualifier and rebuttal produced the lowest results, with mean scores of 8.93 (59.6%) and 8.33 (55.6%), respectively. The standard deviations were relatively similar across the components, although rebuttal showed the greatest dispersion, indicating wider differences in students' ability to anticipate and respond to alternative positions. The descending pattern indicates that students found it easier to state what they believed than to construct a multilayered justification for that belief. Most students could claim that electric vehicles should be supported because they reduce direct exhaust emissions. Fewer students could explain how specific evidence about battery chemistry, degradation, mineral extraction, or recycling logically affected the environmental status of the technology. Even fewer students explicitly restricted their claims or addressed opposing arguments. The component scores reported in Table 3.

Table 3. Students' scores for each argumentation component

Argumentation component	Mean score	Standard deviation	Maximum score	Achievement (%)	Rank
Claim	11.87	2.03	15	79.1	1
Data	11.20	2.01	15	74.7	2
Warrant	10.67	2.02	15	71.1	3
Backing	9.93	2.12	15	66.2	4
Qualifier	8.93	2.02	15	59.6	5
Rebuttal	8.33	2.19	15	55.6	6

The relatively high claim score indicates that the SSI context successfully elicited identifiable positions from almost all participants. Students could generally communicate whether they supported the expansion of electric-vehicle use and identify environmental benefits or limitations. However, the decrease in scores from data to warrant and backing shows that the presence of information did not necessarily result in a scientifically coherent argument. Some students mentioned that batteries contain chemicals, originate from mining, or may become hazardous waste, but did not sufficiently explain the relationship between these facts and their conclusions. A warrant requires students to transform information into reasoning by articulating why the evidence justifies a claim, while backing strengthens that reasoning through relevant disciplinary principles. Namdar and Shen (2016) similarly emphasized that scientific argumentation requires the coordination of claims, evidence, reasoning, and appropriate scientific representations. In electrochemistry, such coordination involves connecting observable technological or environmental phenomena with redox reactions, electron flow, ion movement, electrode changes, and battery degradation. The findings therefore indicate that knowing isolated electrochemical terms was insufficient. Students needed to organize those concepts into causal explanations that could support judgments about a real technological issue. This interpretation is also aligned with chemistry education research that distinguishes the possession of fragmented knowledge from coherent and usable disciplinary understanding (Cooper & Stowe, 2018). Chemistry learning should therefore provide explicit opportunities for students to explain the inferential relationships among evidence, chemical mechanisms, and socially relevant conclusions.

Differences among High-, Moderate-, and Low-Ability Students

The qualitative findings confirmed that the three performance categories represented different levels of argumentative completeness and scientific reasoning. Students in the high category constructed comparatively balanced arguments that incorporated benefits, risks, conditions, and alternative perspectives. M03, for example, supported electric vehicles but argued that their environmental status should be assessed throughout the battery life cycle rather than only during vehicle operation. The student connected the issue with lithium, nickel, and cobalt extraction, battery waste, redox reactions, electrode processes, and performance degradation.

M03 also stated that support for electric vehicles depended on the availability of responsible waste-management and recycling systems. Similarly, M12 recognized that the environmental impact of electric vehicles depended on the source of electricity, the battery-production process, and end-of-life management. These responses contained clear claims, relevant data, scientific warrants, conceptual backing, explicit conditions, and consideration of counterarguments. The arguments were therefore not merely longer than those of other students; they were structurally more interconnected. The high-performing students treated electric vehicles as a conditional sustainability option whose environmental value depended on the broader production and waste-management system.

Students in the moderate category could articulate relevant positions and use basic electrochemical concepts, but their evidence and counterarguments remained general. M02 explained that batteries generated electricity through chemical reactions and electron transfer, yet acknowledged limited understanding of detailed lithium-ion reactions. The student supported electric vehicles provided that battery waste was appropriately processed, but this condition was not supported by a detailed explanation of recycling processes or material recovery. M10 correctly referred to redox reactions and electron flow but explicitly reported difficulty responding to opposing opinions. In the low category, arguments were largely based on everyday assumptions. M04 reasoned that electric vehicles were environmentally preferable simply because they did not use gasoline, while M11 could identify batteries as an application of electrochemistry but could not explain oxidation and reduction processes. Both students had difficulty supplying scientific evidence and constructing rebuttals. These patterns show that differences in overall scores were related to students' capacity to mobilize conceptual knowledge within an argumentative structure. The interviews consequently supported the written-test categorization: high-performing students integrated scientific and environmental reasoning, moderate-performing students applied basic concepts without sufficient depth, and low-performing students relied predominantly on general claims.

The category differences also demonstrate that conceptual knowledge and argumentative competence were mutually related but not identical. Students could remember that batteries involved redox reactions without being able to use this knowledge as backing for an environmental judgment. Conversely, they could identify waste or pollution as relevant concerns without explaining the electrochemical or material basis of those concerns. SSI-based reasoning requires the integration of disciplinary content with the capacity to investigate complexity, question evidence, and evaluate alternative courses of action (Kinslow et al., 2019; Zeidler et al., 2019). Therefore, instruction should not assume that students will automatically transform conceptual knowledge into evidence-based argumentation. Greater scaffolding may be required through evidence tables, argument maps, contrasting claims, guided warrant questions, and structured peer critique. For example, students may be asked not only to identify that spent batteries pose environmental risks but also to explain which materials are involved, how battery degradation affects end-of-life decisions, what evidence supports recycling, and under what conditions recycling provides environmental benefits. Such tasks could help students move from naming scientific concepts to using those concepts as explanatory and evaluative resources.

Weaknesses in Qualifiers and Rebuttals

Qualifier and rebuttal were the two weakest components, indicating that students had difficulty recognizing uncertainty, restricting the scope of their claims, and engaging with competing viewpoints. Although some students used conditional statements such as "provided that battery waste is managed" or "if recycling systems are available," these conditions were frequently stated without further explanation. Students did not always identify how electricity generation, battery chemistry, manufacturing location, vehicle lifetime, recycling technology, or material recovery could modify their conclusions. The weakness was more apparent in rebuttal. Several students could acknowledge that another opinion existed but could not evaluate its scientific strength or formulate a reasoned response. M10 stated, "I can express my own opinion, but when I have to respond to an opposing opinion, I am still confused about choosing the appropriate reason." M11 similarly explained that it was difficult to provide scientific reasons and construct a rebuttal. These responses demonstrate that students experienced rebuttal as an additional task rather than as an integral process of testing the validity of their own arguments. Similar patterns have been reported in SSI research, in which students more readily construct claims and supporting reasons than counterarguments and scientifically justified rebuttals (Aziz & Johari, 2023; Çapkınoğlu et al., 2020; Dawson, 2025).

The weakness of rebuttal is significant because the quality of a socioscientific argument depends on the ability to evaluate more than one plausible interpretation. Electric vehicles provide a particularly suitable context for this process. A claim that they are environmentally beneficial may be challenged by evidence concerning battery production, electricity generation, mining impacts, or end-of-life waste. Conversely, a claim that batteries make electric vehicles environmentally harmful may be challenged by evidence concerning reduced operational emissions, longer battery life, second-use applications, or material recovery. Students must therefore evaluate the strength and limitations of evidence rather than simply select a pro- or anti-technology position. Romine et al. (2017) conceptualized socioscientific reasoning as involving complexity, inquiry, skepticism, and perspective taking, all of which require engagement with uncertainty and alternative positions. Zeidler et al. (2019) likewise argued that SSI learning should encourage reflective judgment and evidence-informed decision-making rather than the reproduction of predetermined answers. The present findings suggest that instructional attention should be directed specifically toward counterargument and rebuttal. Students could be given competing evidence sets, required to write the strongest opposing argument before defending their own position, and asked to revise claims after peer evaluation. Such activities may help students understand rebuttal as a means of strengthening an argument rather than merely disagreeing with another person.

Integration of Electrochemistry and the Environmental Dimensions of Batteries

The interviews revealed that redox reactions and electron flow were the electrochemical concepts most frequently used to discuss electric-vehicle batteries. High- and moderate-performing students generally understood that electricity was produced through oxidation and reduction processes and that electron transfer through the external circuit generated electrical energy. Some students also mentioned anodes, cathodes, ion movement, electrode-material changes, and battery degradation. However, the depth with which these concepts were linked to the SSI varied considerably. High-performing students used electrochemistry to explain why battery performance decreases over repeated use and why degraded batteries eventually require replacement or recycling. In contrast, low-performing students tended to state only that batteries "produce electricity" or are "examples of electrochemistry." They were unable to explain how electrode reactions, ion transfer, material degradation, and battery life were related to environmental consequences. The interview synthesis consequently identified a recurring difficulty: students could state opinions about environmental problems but struggled to connect those opinions with appropriate chemical mechanisms. Claim was generally clear, while data, warrant, and rebuttal became progressively less developed when the explanation required deeper disciplinary knowledge.

The stronger arguments also demonstrated emerging systems-oriented reasoning. M03 argued that claims of environmental friendliness should be assessed across the entire life cycle rather than only during vehicle operation, while M12 considered electricity sources, manufacturing, use, and waste management. This reasoning is scientifically relevant because the sustainability of lithium-ion batteries depends on interconnected processes involving raw-material extraction, cell production, operation, degradation, collection, reuse, and recycling. Recycling may recover valuable materials, but its environmental performance varies according to battery chemistry, processing technology, energy inputs, and recovery efficiency (Ciez & Whitacre, 2019; Jiang et al., 2025; Ma et al., 2024; Mrozik et al., 2021). The issue therefore required students to move between molecular-level electrochemical processes and broader technological and environmental systems. Systems thinking in chemistry education is intended to help learners understand these interactions rather than treating chemical concepts as isolated content (York et al., 2019).

The ability of several students to formulate conditional support for electric vehicles indicates that the SSI context encouraged more nuanced positions than a simple choice between agreement and disagreement. However, this ability was concentrated among students in the high and moderate categories. Many students still evaluated electric vehicles primarily through visible operational characteristics, particularly the absence of exhaust smoke or gasoline consumption. Such reasoning overlooks upstream and downstream processes and may lead to an incomplete environmental judgment. Future electrochemistry learning should therefore integrate chemical representations with life-cycle data, case comparisons, and competing environmental evidence. Students could compare battery chemistries, trace the movement of materials through the battery life cycle, evaluate alternative recycling processes, and construct arguments under different electricity-generation scenarios. These activities would help clarify that scientific conclusions about emerging technologies are conditional on the evidence, boundaries, and assumptions used. The findings ultimately show that the central instructional challenge is not merely enabling students to express opinions. It is supporting them in constructing claims that are connected to credible evidence through explicit electrochemical reasoning, strengthened by relevant theory, appropriately qualified, and defensible against alternative interpretations.

CONCLUSION

This study found that students' argumentation skills in SSI-based electrochemistry learning was generally moderate. Most students could state clear claims and provide basic supporting data, but they had greater difficulty developing warrants, qualifiers, and rebuttals. Claim was the strongest argumentation component, whereas rebuttal was the weakest. High-performing students were able to connect electrochemical concepts with battery production, degradation, waste management, and environmental impacts. In contrast, lower-performing students tended to rely on general opinions and showed limited scientific reasoning. These findings indicate that understanding electrochemical concepts alone is insufficient to produce strong arguments. Electrochemistry learning should therefore provide explicit practice in evaluating evidence, explaining scientific reasoning, considering limitations, and responding to alternative viewpoints.

RECOMMENDATIONS

Electrochemistry learning should provide more practice in using scientific evidence, constructing rebuttals, and evaluating alternative perspectives. Future studies should involve larger samples and experimental designs to examine the effectiveness of SSI-based learning.

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