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Integrating green and sustainable chemistry into high school: contributions of instructional model-based teaching to enhance students' critical reflective thinking

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The integration of Green and Sustainable Chemistry Education (GSCE) into high school fosters students' critical reflection on socio-environmental issues. This study examines how multimodal teaching activities designed around pedagogical models contribute to the development of critically reflective students. A qualitative research design was employed. Instructional model-based activities within the GSCE were implemented with 26 high school students enrolled in a chemistry course at a rural school in Brazil. The students worked in small groups to participate in instructional, reflective, and experimental activities, including a case study (CS) focused on socio-scientific issues related to local water scarcity. Data were collected using multiple instruments, including a CS, classroom observations, and students' written responses. The results indicate that these activities support students' ability to critically analyze environmental problems, recognize their complexity, and reflect on the interrelationships among science, technology, and society. However, limitations were observed regarding students' self-awareness and the translation of critical reflection into behavioral intention, with responsibility often attributed primarily to governmental actors. These findings align with previous studies reporting challenges in achieving sustained engagement in sustainable practices. Overall, the study underscores the role of instructional models in structuring the integration of GSCE in secondary education and in fostering critical reflection, while highlighting the need for pedagogical strategies that further strengthen students' active participation in sustainability.

Sustainability spotlight

Integrating Green and Sustainable Chemistry Education (GSCE) into secondary education is directly linked to SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production). However, sustainability education in rural school contexts remains underrepresented, despite these communities facing acute socio-environmental challenges such as water scarcity, which is directly linked to SDG 6 (Clean Water and Sanitation). To advance Education for Sustainable Development, teaching approaches must be context-based and equitable, fostering students' critical reflection and agency. This work examines how multimodal activities support students' understanding of the interconnections between chemistry, society, and sustainability. While promoting critical reflection, the findings also reveal persistent challenges in translating reflection into individual action, highlighting key directions for strengthening sustainability oriented chemistry education.

Introduction

Green and Sustainable Chemistry Education (GSCE) has emerged as a relevant interdisciplinary field that seeks to align the teaching of chemistry with environmental responsibility, ethical reflection, and social justice. This approach contributes not only to the understanding of chemical principles but also to the development of critical and active citizenship, guided by sustainability and inclusion. Although international frameworks such as the United Nations' Sustainable Development Goal 4 (SDG 4) emphasize inclusive and equitable quality education, GSCE offers valuable pathways to rethinking science education in diverse sociocultural contexts, by encouraging reflection on sustainability-related challenges.

Education for sustainability (EfS), or Education for Sustainable Development (ESD), as it is usually named, encompasses

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bringing awareness to sustainability issues and developing knowledge to address those issues, by guiding new research on relevant topics or empowering society in general to participate in decision making. A set of key competencies is needed for bringing about this empowered subject and can be grouped in three domains as follows:[1–3]

1. Cognitive domain:
(a) Systems thinking competency.
(b) Anticipatory competency.
(c) Normative competency.
(d) Critical thinking competency.
2. Socio-emotional domain:
(a) Collaboration.
(b) Self-awareness.
3. Behavioural domain:
(a) Strategic competency.
(b) Integrated problem-solving competency.

In this sense, GSCE encompasses environmental, social, and economic dimensions of sustainability, and its application in the classroom should be guided by didactic models capable of articulating these layers. According to Sjöström, Eilks and Talanquer (2020, pp. 911),[4] didactic models aim "to guide teacher thinking when making educational decisions, before, during, and after teaching practice." They can be used as analytical tools to reflect upon teaching activities or guiding principles, helping teachers to establish connections between theoretical views and teaching practice.

Didactic models on EfS may also help to structure its rapid growth. According to a review in Web of Science,[5] the first paper of EfS (and related terms) was published in 1993. Fifty-one papers were published in 2009, 106 in 2014, 203 in 2018, and 451 in 2019, showing that the output is doubling at an increasing pace.

However, literature reviews point out the scarcity of research on teaching and learning activities in EfS. In the 153 records on EfS in higher education retrieved from Education Research Complete and the Education Resource Information Center (ERIC), only 16 addressed specific teaching and learning activities.[6] Green chemistry teaching, on the other hand, is more balanced, having considerable output addressing reports and proposals of teaching activities, as well as research reflecting upon its nature, limits, and objectives.[7–9]

In this context, Sandri and Santin Filho (2019)[10] proposed three instructional models for GSCE, organized along a continuum that ranges from a technical-instrumental orientation to a critical perspective. These models are structured around four dimensions – didactic approach, teacher's role, timing and frequency of implementation, and educational objectives – which together provide a coherent framework for the design and analysis of teaching activities.[10] Notably, these models were originally conceived for secondary school contexts, which aligns with the scope of the present study.

Consistent with this pedagogical framework, studies in EfS also emphasize the importance of adopting active methodologies.[11–18] Vilmala *et al.* (2022)[12] reported that problem- or project-based learning activities are suitable for EfS, as they enable the development of core competencies, such as strategic and integrated problem-solving competencies. Similarly, Clapson *et al.* (2025)[13] demonstrated that inquiry-based and gamified active learning activities grounded in green chemistry principles, such as systems thinking and life cycle analysis, can effectively engage learners in critically examining sustainability challenges and connecting chemical research to societal and policy contexts. Moreover, an analysis of green chemistry education papers published in the Journal of Chemical Education up to 2019 revealed that 21% of studies employing non-traditional teaching strategies emphasized the active role of learners, frequently through problem- and project-based learning approaches.[9]

Among them, the case study (CS) method stands out for its potential to engage students in the resolution of real-world problems, fostering critical thinking, collaborative work, and the application of chemical knowledge to socially relevant issues. In parallel, tools such as the Green Star[19–21] – an evaluative metric of green chemistry – can contribute to strengthening the connection between practical chemistry and sustainability criteria, making such learning more tangible and meaningful.

In this context, our study is guided by the following research question: how do instructional model-based teaching activities in green and sustainable chemistry support the development of critical reflective thinking among secondary school students? Our objective is to examine the potential of the instructional model proposed by Sandri and Santin Filho (2019)[10] to foster students' critical reflective thinking and to identify elements that allow inferences about this developmental process within a rural educational context.

To date, there is no empirical research that explicitly examines the use of instructional model-based teaching to enhance students' critical reflective thinking in rural high school contexts. This gap in the literature underscores the originality and relevance of the present study.

Research design and methods

Pedagogical approach and participants

For this study, a participant-based approach was employed to investigate the effects of instructional model-based teaching to students' critical reflection. Specifically, the pedagogical framework of the Three Pedagogical Moments (problematization, knowledge organization, and knowledge application) proposed by Delizoicov *et al.* (2021),[22] along with the methodological guidelines outlined by Sandri and Santin Filho (2019),[10] were adopted. Within this framework, instructional activities were carried out with a group of 26 high school students enrolled in an integrated technical course in Environmental Studies at the Federal Institute of Education, Science, and Technology of Paraiba (IFPB), Campus Sousa, Brazil, a campus located in a predominantly rural region.

All participants voluntarily took part in the study and provided informed assent and/or consent. The research was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and was approved by the Human Research Ethics Committees of the University of Campinas

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(protocol number 56608422.6.0000.5404, approved on 16 May 2022) and the IFPB (protocol number 56608422.6.3001.5185, approved on 31 May 2022).

Instruments

Regarding the instruments used in this study, we analysed data using both quantitative and qualitative methods. Specifically, quantitative analysis was employed for the pre- and post-tests to numerically discern trends among the participants. Conversely, qualitative analysis was utilized for data derived from the resolutions of the CS, aiming to comprehend the interpretations and insights derived from the responses.

Questionnaires

Table 1 presents the goals and question types of the pre- and post-tests. All tests were administered individually to ensure anonymity.

The pre-test contained six open-ended questions (SI Appendix A), six closed-ended questions ("yes," "no," "maybe," or "I don't know") (SI Appendix B), and three items on a 5-point Likert scale (SI Appendix C). The post-test contained 20 Likert-scale items (SI Appendix D). No pre-test questions were repeated because each instrument served a distinct purpose: the pre-test assessed initial perceptions, and the post-test captured impressions of the methodological pathways.

Case study (CS) method

Case studies (CS)[23,24] were applied to assess the impact on students' critical learning about green chemistry,[25,26] and the method was used to analyse the texts produced by the class. The CS addressed the issue of water scarcity in the city of Sousa,[27] Brazil, despite the presence of the São Gonçalo Reservoir, which has a maximum capacity of 44.6 million m^3. Although this reservoir is considered sufficient to supply the municipality's population of 65 803 inhabitants, many neighborhoods have reported recurring shortages, generating significant socioeconomic impacts.

To investigate the causes of the problem, the mayor assembled a team composed of a local teacher, a resident, an employee of the water supply company, and the student participant. The narrative presented differing perspectives: inadequate distribution infrastructure and irresponsible domestic water use. Students were then asked to propose ways to identify the main cause of the shortage, to argue for one of the proposed alternatives, and to outline an action plan to promote the conscious use of water among the population. Data analysis focused on the five final texts produced by the class.

The CS on water scarcity in Sousa was used as the central contextual problem guiding the instructional sequence. Throughout the sessions, the chemistry topics addressed in class – such as the principles of green chemistry, organic reactions, green chemistry metrics, and water treatment processes – were progressively connected to the issues raised in the CS. This integration allowed students to apply the scientific concepts discussed in class to analyse the possible causes of the water shortage and to develop evidence-based arguments and proposals for addressing the problem. In this way, the CS functioned as a pedagogical bridge between the curricular chemistry content and the socio-environmental context explored in the activity.

Procedure

The research was implemented over seven sessions, each comprising three 50 minute chemistry classes, totaling 21 lessons. Table 2 details the activities and educational objectives associated with each session. A more detailed description of the lessons, including the alignment between instructional activities, collected data, and analytical procedures, is provided in the SI (Appendix E). These goals were derived from the framework proposed by Sandri and Santin Filho (2019),[10] which enables the systematic analysis of the level at which green chemistry is addressed – classified as technical, intermediate, or critical.

These activities complement one another in creating a rich environment in which sustainability competences (in their cognitive, socio-emotional and behavioural dimensions) can flourish. The CS provided students with the opportunity to develop collaborative competences by learning from others, understanding and respecting their needs, perspectives, and actions, and managing conflict within a group. The activity also encouraged students to develop self-awareness when reflecting on actions they could undertake to address water scarcity in the region. Furthermore, they were required to propose a plan to

Table 1 Goals and types of questions in pre- and post-tests[a]

Tests	Types of questions	Goals
Pre-test $N = 15$	Open-ended ($N = 6$) closed-ended ($N = 6$) Likert scale ($N = 3$)	Assess participants' prior knowledge of green chemistry, water-related topics, and their learning strategies, regardless of whether such knowledge or practices were developed in formal or non-formal educational contexts
Post-test $N = 20$	Likert scale ($N = 20$)	Assess participants' perceptions of the methodological pathways and the general issues addressed

[a] N = The number of questions.

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Table 2 Procedural steps and educational objectives

Sessions	Activities developed with the rural students	Educational objectives based on Sandri and Santin Filho (2019)
1	- Presentation of the research procedures - Administration of the pre-test - Implementation of the case study (CS), with the formation of five teams	- To foster conscious, intentional, and critical practice of green chemistry (GC) - To promote education for sustainability
2	- Lessons on the history of GC, its 12 principles, and a review of concepts including physical and chemical transformations, chemical reactions and equations, and the law of conservation of mass - Discussion of the teams' initial CS solution - Completion, in groups, of questions from the brazilian national high school examination (ENEM; Portuguese: Exame Nacional do Ensino Médio) focused on GC	- To disseminate or provide information about GC - To integrate GC into chemistry education - To improve the social perception of chemistry through GC - To encourage conscious, intentional, and critical practice of GC - To promote education for sustainability
3	- Lessons on hydrocarbon reactions - Review of the 12 principles of GC integrated into the instructional content	- To disseminate or provide information about GC - To incorporate GC into chemistry teaching - To improve the social perception of chemistry through GC - To encourage conscious, intentional, and critical practice of GC - To promote education for sustainability
4	- Review of the content covered - Lessons on the water treatment Plant and Toulmin's argument structure - Review of the 12 principles of GC integrated into the instructional content - Discussion of the teams' CS solutions using Toulmin's argument structure	- To disseminate or provide information about GC - To incorporate GC into chemistry teaching - To improve the social perception of chemistry through GC - To encourage conscious, intentional, and critical practice of GC - To promote education for sustainability
5	- Reading of the text "green reactions" - Lessons on GC metrics, emphasizing the environmental factor - Implementation of the educational activity "which industry Am I?" - Review of previously covered content - Discussion of the teams' CS solutions	- To improve the social perception of chemistry through GC - To stimulate conscious, intentional, and critical practice of GC - To promote education for sustainability
6	- Review of previously covered content, including organic reactions and GC metrics - Presentation of CS solutions - Introduction to key laboratory safety standards - Overview of the "green chemistry thematic environment"[28]	- To improve the social perception of chemistry through GC - To encourage conscious, intentional, and critical practice of GC - To promote education for sustainability
7	- Reading of the investigative text about the disaster of Bento Rodrigues in Brazil, caused by the collapse of a mining tailings dam[29] - Conducting the experimental session, inspired by the methodology proposed by Ventapane and Santos (2021)[30] - Administration of the post-test	- To improve the social perception of chemistry through GC - To promote conscious, intentional, and critical practice of GC - To advance education for sustainability

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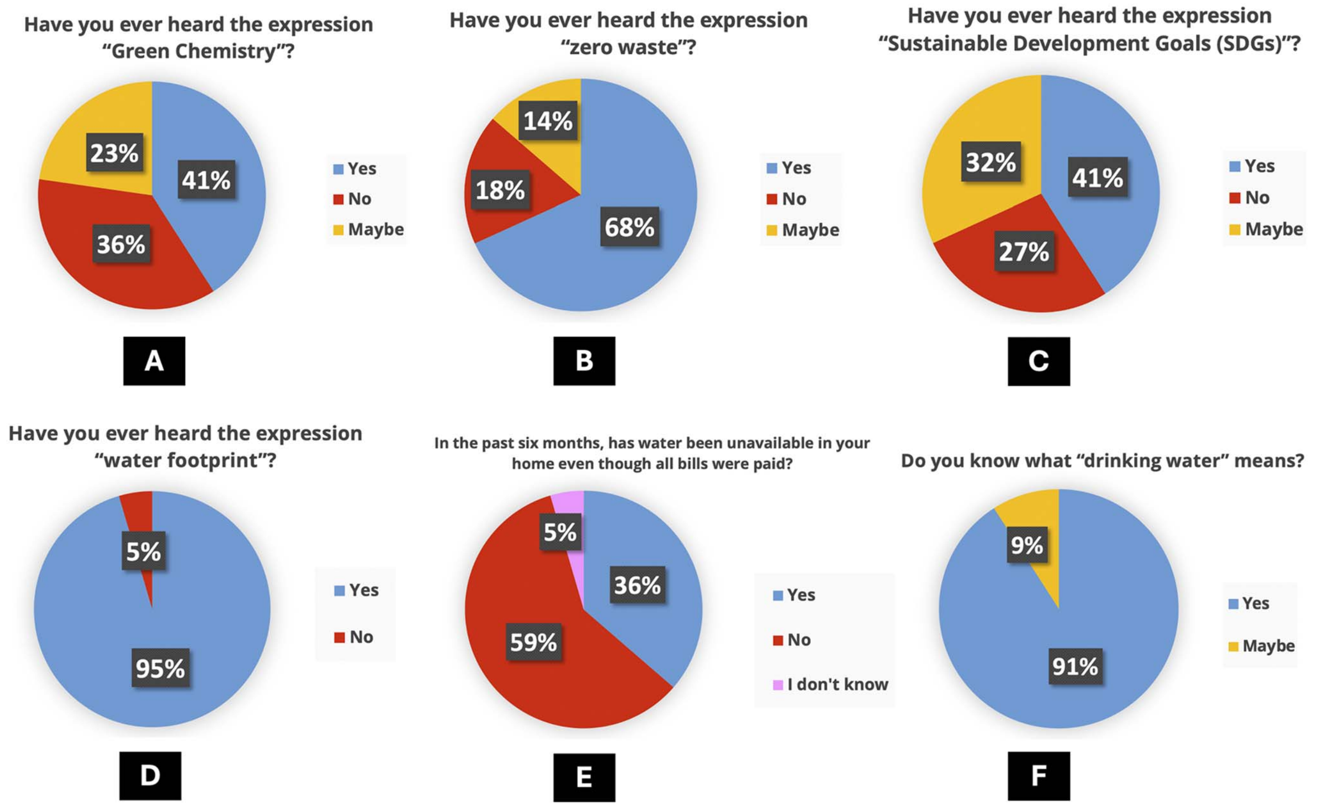

Fig. 1 Responses to the closed-ended questions in the pre-test. (a)–(f) denote individual questions.

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tackle the problem, thereby engaging strategic and integrated problem-solving competences.

Lessons on the 12 principles of green chemistry (GC), GC metrics, and laboratory safety standards were designed to foster anticipatory competences by encouraging students to assess the consequences of actions, address risks and uncertainties, and apply the precautionary principle. Toulmin's model of argumentation supported students in reflecting upon their values, perceptions, and actions, enabling them to adopt a well-founded position within sustainability discourse, that is, to exercise critical thinking competence.

Normative competence was addressed throughout the activities by prompting reflection on the norms and values underpinning action: safe laboratory practices, preventive and precautionary approaches in industry, and tensions between economic values and human rights in the exploitation of natural resources. Taken together, the set of activities enabled students to grasp the interconnectedness of sustainability issues (systems thinking competence) by integrating chemical knowledge, GC practices, and structured argumentation in addressing a concrete problem (such as the CS problem situation).

Data analysis

For the analysis of the pre-test, the accuracy rate was calculated. Additionally, five final written texts produced and presented by the students were examined. The post-test, composed of Likert-scale items, was analysed by determining the frequency distribution of responses for each scale point, thereby reducing potential statistical bias and allowing an assessment of students' perceptions and attitudes.

The process of segmenting these texts into Units of Analysis (UAs) was conducted by the first author. In line with the methodologies proposed by Scheuer *et al.* (2014)[31] and Souza and Queiroz (2018),[32] each UA was defined as a statement that concluded with either a period or a semicolon, which enabled the assessment of students' written output in terms of structure and extent. As suggested by Souza and Queiroz (2018),[32] this study prioritized the quantification of UAs without incorporating a qualitative judgment of the content at this stage. For the qualitative dimension of the analysis, each UA was classified according to the type of evidence employed – whether personal or based on authoritative sources – and its thematic domain, such as scientific, social, environmental, commercial, political, economic, cultural, health-related, or ethical aspects. This type of qualitative categorization has been widely adopted in the literature to characterize student-generated texts. The resulting data were visually represented using graphs and figures, created with software tools like Microsoft Excel.

Findings

Prior knowledge of research terms

Fig. 1 reports the responses to items 1–6 from the survey with closed-ended questions (SI Appendix B), which formed part of

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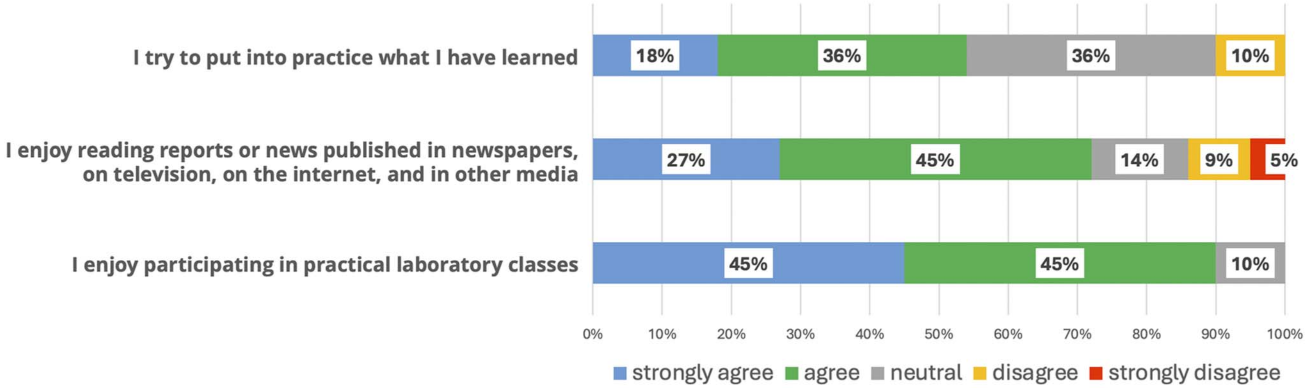

Fig. 2 Responses to questions on a five-point Likert scale in the pre-test.

the pre-test. The objective was to assess the class's prior knowledge regarding some terms or expressions relevant to the research.

The data reveal uneven levels of familiarity with sustainability-related concepts. Awareness of green chemistry was limited, with only 41% reporting prior contact, while 36% had never heard the term and 23% were unsure (Fig. 1A). In contrast, "zero waste" showed broader recognition (68% yes), suggesting higher public visibility (Fig. 1B). Familiarity with the SDGs remained moderate: 41% had heard of them, 32% were uncertain, and 27% reported no prior knowledge (Fig. 1C).

Students demonstrated awareness of "water footprint" (95% yes), indicating that water-related themes are more present in their educational environments (Fig. 1D). This emphasis is consistent with their lived experiences, as 36% reported recent episodes of water unavailability at home despite all bills being paid (Fig. 1E). Finally, understanding of the term "drinking water" was high (91% yes), with only 9% expressing uncertainty (Fig. 1F).

These results indicate that students exhibit familiarity with concepts directly associated with water access and quality, whereas more specialized sustainability terms, particularly those related to green chemistry, remain less recognized. This discrepancy underscores the need for targeted educational actions to broaden students' conceptual understanding within GSCE.

With respect to the open-ended questions in the pre-test (items 1–5, SI Appendix A), the findings also indicate limited prior knowledge of green chemistry and its foundational principles. In response to "What do you think green chemistry might be?", 81% of the students associated the term with broadly environmental or ecological themes. However, as discussed by Andrade and Zuin (2023),[26] these interpretations are conceptually inaccurate, since green chemistry is defined by the intentional design of products and processes that reduce or eliminate the use and generation of hazardous substances[33] – an aspect absent from all responses. Additionally, 15% of the students reported not knowing how to answer the question, and 4% left the item blank.

A similar pattern emerged for the question "What is the first principle of green chemistry?". Only 12% of the learners provided environmentally oriented yet vague or imprecise answers, whereas 84% stated that they did not know the principle, and 4% left the item blank. Notably, none of the students identified the correct principle – prevention, which emphasizes minimizing waste at its source.[33] These results collectively reflect a lack of prior conceptual understanding of green chemistry.

In response to "Does the chemical industry bring benefits to society? Justify your answer.", 82% of the students answered affirmatively, emphasizing technological advances, improved quality of life, and pharmaceutical production. Illustrative responses included: "many things would not be possible without chemistry" and "it is through the chemical industry that medicines are produced for the population." In contrast, 14% reported not knowing how to answer, and 4% left the item blank. Overall, students viewed the chemical industry as beneficial, although justifications remained predominantly practical rather than socio-environmental.

Conversely, when asked "Does the chemical industry bring harm to society? Justify your answer.", 65% responded affirmatively, most frequently citing environmental pollution, inadequate waste disposal, and risks to human health. Examples included statements that the industry generates "pollution released into the soil and air" and that "chemical waste discarded improperly can worsen environmental conditions." Additionally, 4% stated that it does not bring harm, 4% responded "maybe," 23% reported not knowing, and 4% left the item blank. These results indicate that perceived harm is framed primarily in environmental terms, with limited recognition of broader systemic or socio-economic aspects.

Table 3 Number of Units of Analysis (UAs) per group of students

Group	Number of units of analysis (UAs)
1	19
2	15
3	27
4	14
5	16

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Based on the students' responses regarding the importance of proper water treatment, 45% emphasized issues related to disease prevention and human health, while 41% highlighted aspects associated with safe water consumption. Illustrative statements included: "the importance of proper water treatment is to avoid diseases caused by polluted water," and "water must be treated because untreated water can cause serious health problems." A smaller portion of responses corresponded to "I don't know" (5%) and blank answers (5%). It is important to note that these percentages do not total 100%, as some students articulated ideas that fit into more than one category – for example, simultaneously addressing health risks and consumption-related concerns.

General perceptions regarding learning strategies

Fig. 2 reports the findings from the survey assessment on a 5-point Likert scale (SI Appendix C), which also formed part of the pre-test. The analysis reveals a predominantly positive response pattern.

For the statement "I try to put into practice what I have learned," 18% of students strongly agreed, 36% agreed, 36% were neutral, and 10% disagreed, indicating moderate adherence to applying learned content. Regarding interest in reading scientific or informational media, 27% strongly agreed and 45% agreed, while 14% were neutral, 9% disagreed, and 5% strongly disagreed, reflecting overall positive engagement with informational sources. The most positive evaluation was observed for enjoyment of laboratory classes, with 45% strongly agreeing, 45% agreeing, and 10% neutral, demonstrating a preference for practical learning experiences.

When students were asked, "What could I do to learn more and learn better?" (item 6, SI Appendix A), 60% of the responses emphasized individual study strategies, including reviewing content, completing exercises, and seeking additional information. Another 15% highlighted the importance of practical activities for consolidating learning, as illustrated by the statement, "Putting into practice everything that is taught, I believe, is the best way to learn." Additionally, 20% referred to study planning and organization, and 5% mentioned increased participation in class as a means to improve learning.

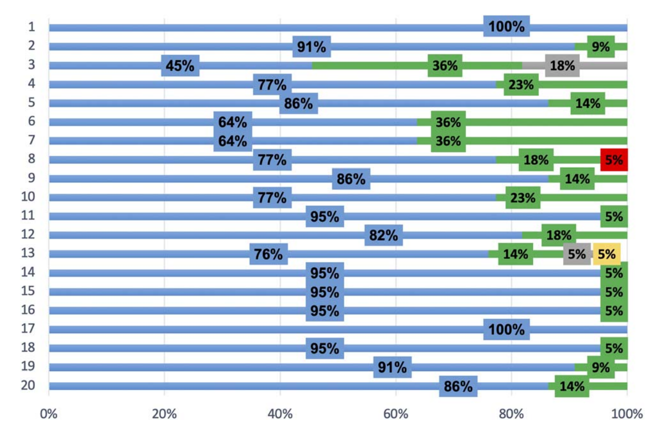

Fig. 3 Responses to items 1–20 on a five-point Likert scale in the final assessment.

Written productions

The analysis of the written productions revealed substantial variability in the number of Units of Analysis (UAs) generated by the student teams. As shown in Table 3, the class collectively produced 91 UAs.

Group C presented the highest number of UAs (27), whereas Group D produced the fewest (14). This discrepancy is largely attributed to the structure and descriptive depth of the texts. In particular, Group C provided a detailed description of a technological device proposed as a solution to water waste, using short, segmented sentences to outline its objectives and operational mechanisms. Because UAs were defined as statements ending with a period or semicolon, the more fragmented structure of Group C's text resulted in a higher UA count. It is also noteworthy that this team was the only group to incorporate pictographic or visual inscriptions into its proposed solution, a feature that may have contributed to the elaboration and segmentation of its written argumentation.

Regarding the analysis of evidence sources,[32] all teams presented some form of evidence in their written texts. Overall, evidence based on authoritative sources was more frequently observed than evidence of a personal nature. Concerning the nature of the arguments, a predominance of social and environmental arguments was identified. Specifically, 52 units of analysis (UAs) were classified as social, while 32 were classified as environmental. This pattern is likely attributable to the inherently controversial nature of the issue and the focus on collective well-being.

Final perceptions regarding research methods

Fig. 3 shows that the 20 Likert-scale items (SI Appendix D) demonstrate a marked predominance of positive evaluations concerning the classes, the case study, and the overall educational experience. In nearly all items, responses were predominantly concentrated in the strongly agree and agree categories.

Regarding conceptual understanding, all students strongly agreed that the classes improved their understanding of green chemistry (item 1). Most also reported gains in organic chemistry, with 91% strongly agreeing and 9% agreeing (item 2). For aquatic chemistry, responses were more distributed: 45% strongly agreed, 36% agreed, and 18% remained neutral (item 3). In addition, 77% strongly agreed and 23% agreed that the classes encouraged more conscious water use in daily life (item 4).

Items focused on scientific and cognitive skills also received high endorsement. Students indicated that the CS enhanced their argumentation skills (86% strongly agree, 14% agree; item 5) and scientific thinking (64% strongly agree, 36% agree; item 6). The same pattern was observed for the development of a proactive stance toward issues involving drinking water distribution in their region (64% strongly agree, 36% agree; item 7).

Regarding collaborative work, 77% strongly agreed and 18% agreed that group activities promoted responsibility and

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citizenship, although 5% strongly disagreed (item 8). Students also reported that group work facilitated communication and shared meaning-making (86% strongly agree, 14% agree; item 9). Organizational aspects of the case were positively evaluated: 77% strongly agreed and 23% agreed on the importance of clear assessment criteria (item 10), and nearly all students valued the professor's role in organizing and evaluating the case (95% strongly agree, 5% agree; item 11). Moreover, 82% strongly agreed and 18% agreed that the time allotted for solving the case was adequate (item 12).

Perceptions of teamwork were further reflected in item 13 : 76% strongly agreed, 14% agreed, 5% were neutral, and 5% disagreed that team members were important for solving the case. Items related to socio-environmental awareness also received strong endorsement. Students strongly agreed that green chemistry classes strengthened their awareness of responsible consumption at local and global levels (95% strongly agree, 5% agree; item 14). A similar pattern was observed regarding the belief that sustainable development is a shared mission (95% strongly agree, 5% agree; item 15). Most students also believed that participation in the project could support their performance on the national high school exam (95% strongly agree, 5% agree; item 16).

Finally, items addressing future interest and motivation showed consistently high levels of endorsement. All students strongly agreed that green chemistry should be discussed more broadly in other subjects of their technical program (item 17). They also expressed a desire for more experiments in chemistry classes (95% strongly agree, 5% agree; item 18) and further discussion about human responsibility in sustainable development (91% strongly agree, 9% agree; item 19). Interest in participating in additional case studies was also high, with 86% strongly agreeing and 14% agreeing (item 20).

Discussion

The results indicate that multimodal pedagogical planning supported students' learning processes and engagement with critical thinking within GSCE. The positive evaluations reported by students, together with gains in conceptual understanding, argumentation, and socio-environmental awareness, indicate that the instructional design went beyond a narrow focus on laboratory experimentation, which is often restricted to the macroscopic level.[34–40] Research in chemistry education has highlighted that meaningful learning arises from the integration of multimodal approaches.[35,38,41–47] More recently, scholars have also shared the importance of inclusive representational levels, which broaden access to chemical knowledge by considering linguistic, cognitive, and communicational diversity.[35,48–51] In this sense, the present findings suggest that green chemistry should not be reduced to experimental practices alone, but rather approached as an integrated educational framework that connects chemical knowledge, ethical considerations, and real-world challenges.

An additional and noteworthy contribution of this study lies in the specific educational context investigated. According to the literature review conducted, no previous studies were identified that simultaneously address green chemistry teaching at the secondary school level and within rural school settings. The students' positive perceptions of the methodology, along with their reported learning gains, provide important evidence that such approaches are both feasible and meaningful in contexts that are often underrepresented in educational research. Rather than serving as isolated results, these findings offer a valuable background for future applications and investigations in similar rural or socially vulnerable educational settings, contributing to the expansion of GSCE beyond urban.

The findings also support the potential of GSCE to promote a more critical and reflective approach to chemistry learning, moving away from practices centered on rote memorization of concepts.

Cognitive domain of sustainability competency

Initial results revealed fragmented and intuitive understandings of green chemistry, whereas the final assessment indicated increased awareness of responsible consumption, the societal role of chemistry, and the relevance of sustainability-oriented decision-making. This shift is particularly significant in the Brazilian context, where an increasing emphasis on preparing students exclusively for university entrance examinations has often marginalized broader educational goals.[52–54] While access to higher education remains important, the results reinforce the need to reclaim the broader purpose of education, which extends beyond academic or labor-market preparation toward the formation of critically engaged citizens capable of interpreting and responding to socio-environmental challenges. In this regard, green chemistry emerges as an educational domain for reconnecting chemical knowledge with ethical responsibility and social life.

Regarding critical thinking competency, students predominantly employed social and environmental arguments in their written productions, frequently supported by evidence, suggesting an engagement with the collective implications of the issues discussed. The use of argumentation models, particularly those aligned with Toulmin's framework,[55,56] appears to have supported students in structuring claims, justifications, and conclusions, thereby strengthening their capacity for reasoned decision-making. Through the CS, students were encouraged to analyze complex problems, negotiate meanings collaboratively, and reflect on local challenges related to water access and management, all of which are central elements of critical citizenship education.

Anticipatory competency is hinted when students agree that green chemistry should be discussed more broadly in other subjects of their technical program. As prevention is a core principle in GC, its insertion throughout curriculum may help students to develop green and sustainable practices. The desire of students for further discussion about human responsibility in sustainable development may signals the systemic nature of sustainability issues. However, we should investigate further the development of these competencies.

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Socio-emotional and behavioural domains of sustainability competency

Students reported in the final assessment that group work facilitated communication and shared meaning-making and that team members were important for solving the case. This shows appreciation for collaborative work and a possible development of collaboration competency. Students also revealed signs of strategic competency by stating that sustainable development is a shared mission, demanding coordinated actions among whole society.

CS analyses also revealed important limitations regarding students' self-reflection and sense of responsibility for social action. While learners were able to identify socio-environmental problems and articulate well-founded arguments, many tended to attribute responsibility for solutions exclusively to governmental authorities. This perspective indicates difficulties in recognizing their own potential roles as active citizens – whether through social mobilization, political engagement, or the development of social technologies aimed at addressing local problems. Such limitations are not unique to this study. Previous research in ESD has shown that, although knowledge acquisition and attitudinal change are frequently achieved, self-awareness and behavioral change are considerably more difficult to promote. Studies often report inertia toward action, even when students demonstrate increased understanding and positive attitudes toward sustainability.[6] Despite UNESCO's emphasis on behavioral learning objectives as central to ESD, these outcomes remain among the least achieved, underscoring the complexity of behavior intention and the need for educational approaches with greater transformational potential.

Finally, considering that the methodology adopted in this study was grounded in the models proposed by Sandri and Santin Filho (2019),[10] it is possible to explicitly address the guiding research question: what are the contributions of activities based on these models to the formation of critical citizenship? The results suggest that these models may contribute by mediating the relationship between chemical knowledge and students' social realities. Their contributions extend beyond conceptual learning to include the development of argumentation skills, socio-environmental awareness, collaborative responsibility, and ethical reflection. Although challenges remain in fostering deeper self-responsibilization and behavioral intention, the activities enabled students to critically evaluate the role of chemistry in society and to recognize sustainability as a shared responsibility. Thus, the findings suggest that instructional models grounded in GSCE can play a significant role in supporting students' critical engagement with socio-environmental issues, particularly when implemented through contextualized, participatory, and problem-oriented pedagogical designs.

Rural context as a mediating factor

The rural educational context in which this study was conducted represents an important mediating factor in interpreting students' perceptions of socio-environmental issues and their attributions of responsibility for addressing them. In Brazil, rural schools have historically provided technical training aligned with the socio-economic and environmental realities of local communities.[59] Despite their relevance, rural educational settings remain under-represented in chemistry education research, particularly in studies addressing GSCE.

Educational practices in these institutions have traditionally integrated theoretical instruction with practical activities related to agricultural production and environmental management. This approach seeks to connect scientific knowledge with the concrete experiences of students living in rural environments.

Within this context, students' educational experiences are often directly connected to environmental challenges such as water availability, resource management, and agricultural practices. Consequently, the rural setting functions not merely as a background characteristic but as a mediating factor that influences how students interpret sustainability challenges and attribute responsibility for addressing them. In semi-arid regions of Brazil, where communities frequently face structural limitations related to water infrastructure and resource governance, these contextual conditions may contribute to students attributing responsibility primarily to institutional or governmental actors, while simultaneously fostering awareness of the social and environmental implications of sustainability-related decisions.

Limitations

This study examined the implementation of instructional model-based green and sustainable chemistry teaching activities in a rural high school context, using a Likert-scale instrument alongside the CS method to explore students' responses and reflective processes. However, several limitations should be acknowledged. The research involved a small sample of 26 high school students from a single rural school in Brazil, which limits the transferability of the findings to other rural educational contexts. In addition, the limited sample size precluded the use of robust statistical analyses. Another limitation is that the study did not analyze the complexity of students' written arguments, which could have provided deeper insights into their reasoning processes and the development of critical reflection.

Furthermore, potential threats to validity should be considered. Students' responses may have been influenced by social desirability, as participants might have provided positive evaluations of sustainability-related learning activities because these themes are socially valued. Moreover, some items in the end-of-class Likert-scale instrument may have been formulated in ways that could guide students' responses, and the instrument did not include reverse-coded items that might help reduce response bias. In addition, maturation effects cannot be fully ruled out, since students' reflective capacities may naturally develop over time during their schooling. Finally, contextual, or external events related to environmental issues in the region during the study period may also have influenced students' perceptions and responses.

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Recommendations

The findings indicate that GSCE can meaningfully support the development of students' critical reflection in high school contexts. In this sense, the recommendations presented here are oriented toward strengthening pedagogical practices that foster reflective engagement with socio-environmental issues, as well as toward evaluating specific instructional models and broader policy outcomes.

Emphasize the three principles of inclusive green and sustainable chemistry education (IGSCE)[35]

These principles are designed to guide reflection, design, and implementation of inclusive pedagogical materials and approaches.[35,57] They include: (i) embracing student-centered learning; (ii) promoting instruction across the five levels of chemical representation; and (iii) adapting the curriculum to enable students to apply their academic skills meaningfully to real-world contexts through supportive teaching and social engagement. In addition to the evidence provided in the present study, prior research has also demonstrated positive impacts from the application of the Triangular Bipyramid Metaphor (TBM) in educational contexts.[41,42,58,59] We concur with these researchers in recognizing that inclusive instructional approaches offer significant opportunities for educational interventions aimed at increasing the participation of all students in chemistry education.

From a pedagogical perspective, the findings of the present study suggest opportunities for future micro-interventions grounded in the principles of IGSCE. Such interventions may include short student-centered activities, tasks that explicitly address the five levels of chemical representation, and reflective discussions connecting chemical concepts to local socio-environmental issues. These practices can support the meaningful application of academic knowledge to real-world contexts and further strengthen students' critical reflective thinking.

Implement policies in rural settings that foster interest in green and sustainable chemistry

Policy-oriented research has increasingly recognized the importance of institutional and governmental frameworks in supporting the integration of green and sustainable chemistry into educational systems.[60,61] Initiatives such as the Green Chemistry Commitment (GCC)[62,63] illustrate how coordinated policy instruments can align educational institutions around shared objectives related to sustainability in chemistry education. However, comparable policy-driven actions remain limited in rural educational contexts.[64,65] This gap underscores the need for the development and implementation of targeted educational policies that explicitly address the structural, geographic, and socio-economic characteristics of rural schools. Such policies should support long-term outreach programs, foster partnerships between educational institutions and local communities, and allocate resources to ensure sustained engagement with green and sustainable chemistry. In doing so, policy frameworks can play a central role in strengthening the integration of chemistry education with broader societal and sustainability goals in rural settings.

Further research into sustainability competencies

Sustainability competencies 1–2 was a good theoretical framework to analyse educational results. However, we have not prepared the research instruments on the basis of this theory. Therefore, we feel sorry to acknowledge we could not analyse deeply, with robust evidence, the development of these competencies. Future research should take them into consideration.

Conclusions

This study provided contributions to the integration of GSCE into rural secondary education through teaching activities designed based on instructional models, with an emphasis on fostering students' critical reflection. Grounded in a qualitative approach, the research engaged 26 high school students from a rural school in Brazil and included instructional activities, group-based written productions, reflective tasks, and a laboratory activity oriented toward sustainability.

The results suggest that instructional model-based activities in GSCE can support students' engagement with socio-environmental issues and stimulate critical reflection. From a sustainability perspective, this study highlights the importance of the GSCE in rural contexts, as it supports students' critical engagement with socio-environmental challenges closely linked to their local environmental, social, and economic realities. The analysis of learners' responses and written productions suggests the development of reflective thinking, as they were able to mobilize scientific, environmental, and ethical perspectives when discussing sustainability-related problems. Furthermore, the laboratory activity provided opportunities for students to connect chemical knowledge with sustainability practices, strengthening contextualized learning.

Author contributions

Conceptualization, C. A. D. S. J.; methodology, C. A. D. S. J.; validation, C. A. D. S. J.; formal analysis, C. A. D. S .J.; investigation, C. A. D. S. J.; resources, C. A. D. S. J.; data curation, C. A. D. S. J., L. V. M, C. A. M., G. G. J., and D. P. D. J.; writing – original draft preparation, C. A. D. S. J.; writing—review and editing, C. A. D. S. J., L. V. M., C. A. M., G. G. J., and D. P. D. J.; visualization, C. A. D. S. J., L. V. M., C. A. M., G. G. J.; and D. P. D. J.; supervision; G. G. J., and D. P. D. J.; project administration, C. A. D. S. J., G. G. J. and D. P. D. J. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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Data availability

Data collected for this study have not been made publicly available owing to ethical considerations. Our research participants have consented to share their data only with the researchers directly involved in this project.

The data supporting this article has been included as part of the supplementary information (SI). See DOI: https://doi.org/10.1039/d5su00964b.

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Notes and references

1 A. Wiek, A. Xiong, K. Brundiers and S. van der. Leeuw, Integrating Problem- and Project-Based Learning into Sustainability Programs, *Int. J. Sustain. High Educ.*, 2014, **15**(4), 431–449, DOI: 10.1108/IJSHE-02-2013-0013.

2 UNESCO, *Education for Sustainable Development Goals: Learning Objectives*, UNESCO, 2017, DOI: 10.54675/CGBA9153.

3 A. Wiek, L. Withycombe and C. L. Redman, Key Competencies in Sustainability: A Reference Framework for Academic Program Development, *Sustain. Sci.*, 2011, **6**(2), 203–218, DOI: 10.1007/s11625-011-0132-6.

4 J. Sjöström, I. Eilks and V. Talanquer, Didaktik Models in Chemistry Education, *J. Chem. Educ.*, 2020, **97**(4), 910–915, DOI: 10.1021/acs.jchemed.9b01034.

5 C. Yang and Q. Xiu, A Bibliometric Review of Education for Sustainable Development, 1992–2022, *Sustainability*, 2023, **15**(14), 10823, DOI: 10.3390/su151410823.

6 B. Algurén, How to Bring About Change – A Literature Review About Education and Learning Activities for Sustainable Development, *Discourse Commun. Sustain. Educ.*, 2021, **12**(1), 5–21, DOI: 10.2478/dcse-2021-0002.

7 C. A. Marques, M. C. M. Sandri, L. V. Marcelino, E. D. S. Dias and A. A. S. C. Machado, Green Chemistry Teaching: A Panorama from Brazilian Authors, *ACTIO: Docência Ciênc.*, 2023, **8**(3), 1–27, DOI: 10.3895/actio.v8n3.17573.

8 L. V. Marcelino, E. D. S. Dias, P. L. Rüntzel, J. C. L. Milli, J. S. Santos, L. C. A. B. Souza and C. A. Marques, Didactic Features Specific to Green Chemistry Teaching in the Journal of Chemical Education, *J. Chem. Educ.*, 2023, **100**(7), 2529–2538, DOI: 10.1021/acs.jchemed.2c01091.

9 C. A. Marques, L. V. Marcelino, É. D. S. Dias, P. L. Rüntzel, L. C. A. B. Souza and A. Machado, Green Chemistry Teaching for Sustainability in Papers Published by the Journal of Chemical Education, *Quim. Nova*, 2020, **43**(10), 1510–1521, DOI: 10.21577/0100-4042.20170612.

10 M. C. M. Sandri and O. Santin Filho, Os Modelos de Abordagem Da Química Verde No Ensino de Química, *Educ. Quím.*, 2019, **30**(4), 34, DOI: 10.22201/fq.18708404e.2019.4.68335.

11 M. D. M. López-Fernández, M. J. Cano-Iglesias and A. J. Franco-Mariscal, Chemistry Inquiry Conducted by Secondary School Students into Material Degradation in the Context of Sustainability, *RSC Sustain.*, 2025, **3**(9), 3997–4019, DOI: 10.1039/D5SU00176E.

12 B. K. Vilmala, I. Karniawati, A. Suhandi, A. Permanasari and M. Khumalo, A Literature Review of Education for Sustainable Development (ESD) in Science Learning: What, Why, and How, *J. nat. sci. integr.*, 2022, **5**(1), 35, DOI: 10.24014/jnsi.v5i1.15342.

13 M. L. Clapson, G. Bannard, G. Daliaho, J. Hong, E. Davy, J. Pitsiaeli, C. S. Durfy and S. Schechtel, Waving the Green Flag: Incorporating Sustainable and Green Chemistry Practices into Research and Education, *RSC Sustain.*, 2025, **3**(10), 4492–4503, DOI: 10.1039/D5SU00554J.

14 J. J. A. Idul, Q. M. I. Jaculbe, N. S. Lucine, M. D. Canama, M. D. Galve, C. L. Sayson, M. P. Suico, K. Z. D. Santiago and A. M. P. Walag, Green Modules: Integrating Green and Sustainable Chemistry Principles to Secondary Chemistry Modules through Process-Oriented Guided Inquiry Learning, *J. Chem. Educ.*, 2025, **102**(3), 1104–1116, DOI: 10.1021/acs.jchemed.4c01360.

15 L. Mammino, Cross-Bridging Green Chemistry Education and Environmental Chemistry Education, *Sustain. Chem. Environ.*, 2025, **9**, 100195, DOI: 10.1016/j.scenv.2024.100195.

16 A. Teplá, J. Dachauer, M. Zodl, R. Steininger and A. Lembens, Integrating Green Chemistry into Austrian Secondary Education Using the Context of Wood Biorefinery, *Chem. Teach. Int.*, 2025, **7**(4), 681–693, DOI: 10.1515/cti-2025-0010.

17 O. B. Akinsipo and O. H. Anselm, Challenges and Opportunities for Implementing Green Chemistry in Nigerian Universities: Educational and Policy Perspectives, *Sustain. Circ. NOW*, 2025, **2**, a25341903, DOI: 10.1055/a-2534-1903.

18 S. Aydin Gunbatar, B. Ekiz Kiran, Y. Boz and E. S. Oztay, A Systematic Review of Green and Sustainable Chemistry Training Research with Pedagogical Content Knowledge Framework: Current Trends and Future Directions, *Chem. Educ. Res. Pract.*, 2025, **26**(1), 34–52, DOI: 10.1039/D4RP00166D.

19 R. C. C. Duarte, M. G. T. C. Ribeiro and A. A. S. C. Machado, Using Green Star Metrics To Optimize the Greenness of Literature Protocols for Syntheses, *J. Chem. Educ.*, 2015, **92**(6), 1024–1034, DOI: 10.1021/ed5004096.

20 A. Machado, Introdução Às Métricas Da Química Verde – Uma Visão Sistêmica, *Editora da UFSC: Florianópolis*, 1st edn, 2014.

21 M. G. T. C. Ribeiro, D. A. Costa and A. A. S. C. Machado, Uma Métrica Gráfica Para Avaliação Holística Da Verdura de Reacções Laboratoriais - "Estrela Verde.", *Quim. Nova*, 2010, **33**(3), 759–764, DOI: 10.1590/S0100-40422010000300050.

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This article is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence.

22 D. Delizoicov, J. A. Angotti and M. M. Pernambuco, *Ensino de Ciências: Fundamentos e Métodos*, Cortez, São Paulo, 5st edn, 2021.
23 F. M. Bernardi and M. S. Pazinato, The Case Study Method in Chemistry Teaching: A Systematic Review, *J. Chem. Educ.*, 2022, **99**(3), 1211–1219, DOI: 10.1021/acs.jchemed.1c00733.
24 C. F. Herreid, What Makes a Good Case?, *J. Coll. Sci. Teach.*, 1998, **27**(3), 163–165.
25 R. S. Andrade and V. G. Zuin, Formative Dimensions for Green and Sustainable Chemical Education: A Qualitative Evaluation Tool of the Formative Level of Experimental Processes, *J. Chem. Educ.*, 2023, **100**(6), 2281–2291, DOI: 10.1021/acs.jchemed.3c00053.
26 R. da. S. Andrade and V. G. Zuin, A Alfabetização Científica Em Química Verde e Sustentável, *Educ. Quím. Punto Vista.*, 2023, **7**, 1–15.
27 J. R. A. de. Lima, M. Pereira, C. A. da, C. J. V. Silva, K. B. Ibiapina and C. M. de. Souza, Saneamento Básico No Brasil e No Município de Sousa-PB, *Rev. Foro*, 2022, **15**(4), 1–16, DOI: 10.54751/revistafoco.v15n4-009.
28 P. L. Rüntzel and C. A. Marques, Ambiente Temático Virtual de Química Verde Para Simulações de Sínteses No Ensino de Química Na Perspectiva Do Desenvolvimento Sustentável, *Quim. Nova Esc.*, 2022, **44**(2), 183–193, DOI: 10.21577/0104-8899.20160308.
29 G. W. Fernandes, F. F. Goulart, B. D. Ranieri, M. S. Coelho, K. Dales, N. Boesche, M. Bustamante, F. A. Carvalho, D. C. Carvalho, R. Dirzo, S. Fernandes, P. M. Galetti, V. E. G. Millan, C. Mielke, J. L. Ramirez, A. Neves, C. Rogass, S. P. Ribeiro, A. Scariot and B. Soares-Filho, Deep into the Mud: Ecological and Socio-Economic Impacts of the Dam Breach in Mariana, Brazil, *Natureza & Conservação*, 2016, **14**(2), 35–45, DOI: 10.1016/j.ncon.2016.10.003.
30 A. L. de S. Ventapane and P. M. L. dos. Santos, Aplicação de Princípios de Química Verde Em Experimentos Didáticos: Um Reagente de Baixo Custo e Ambientalmente Seguro Para Detecção de Íons Ferro Em Água, *Quim. Nova*, 2021, **43**(2), 201–205, DOI: 10.21577/0104-8899.20160253.
31 O. Scheuer, B. M. McLaren, A. Weinberger and S. Niebuhr, Promoting Critical, Elaborative Discussions through a Collaboration Script and Argument Diagrams, *Instr. Sci.*, 2014, **42**(2), 127–157, DOI: 10.1007/s11251-013-9274-5.
32 N. D. S. Souza and S. L. Queiroz, Quadro Analítico Para Discussões Argumentativas Em Fóruns On-Line: Aplicação No Ensino de Química, *Investig. ensino ciênc.*, 2018, **23**(3), 145, DOI: 10.22600/1518-8795.ienci2018v23n3p145.
33 P. T. Anastas and J. C. Warner, *Green Chemistry*, Oxford University PressOxford, New York, 2000, DOI: 10.1093/oso/9780198506980.001.0001.
34 C. A. Da Silva Júnior, C. Morais, D. P. de. Jesus and G. Girotto Júnior, The Role of the Periodic Table of the Elements of Green and Sustainable Chemistry in a High School Educational Context, *Sustainability*, 2024, **16**(6), 2504, DOI: 10.3390/su16062504.
35 C. A. Da Silva Júnior, G. Girotto Júnior, C. Morais and D. P. de. Jesus, Green Chemistry for All: Three Principles of Inclusive Green and Sustainable Chemistry Education, *Pure Appl. Chem.*, 2024, **96**(9), 1299–1311, DOI: 10.1515/pac-2024-0245.
36 V. Talanquer, Macro, Submicro, and Symbolic: The Many Faces of the Chemistry "Triplet.", *Int. J. Sci. Educ.*, 2011, **33**(2), 179–195, DOI: 10.1080/09500690903386435.
37 C. Widyantoro, J. Y. Han, J. S. H. Ong, K. H. Goh and F. M. Fung, Teaching Sustainability through Green Chemistry: An Experiential Learning Approach, *J. Chem. Educ.*, 2025, **102**(7), 2743–2754, DOI: 10.1021/acs.jchemed.4c01476.
38 A. L. de. Quadros, *Representações Multimodais No Ensino de Ciências: Compartilhando Experiências*, CRV, Curitiba, 2020, Vol. **1**.
39 T. Schwantes, D. Medina, B. Morgan and A. Banerjee, Green Beginnings: Creating an Affordable Advanced Enquiry-Based Experimental Nanochemistry Learning Module with Catalytically Active 'Green' Iron Oxide Nanoparticles (IONPs), *RSC Sustain.*, 2025, **3**(8), 3437–3447, DOI: 10.1039/D5SU00083A.
40 J. D'Souza Metcalf, R. K. Winkless, A. Robinson, S. C. Smith, A. R. Rickard and T. J. Dillon, Practical Atmospheric Photochemical Kinetics for Undergraduate Teaching and Research, *RSC Sustain.*, 2025, **3**(11), 5146–5154, DOI: 10.1039/D5SU00681C.
41 J. G. G. Queiroz, J. M. Martins, J. R. G. Lopes, A. S. Jacinto and C. A. Da Silva Júnior, Formação de Professores e Inclusão: Metáfora Da Bipirâmide Triangular No Planejamento de Aulas Inclusivas de Química Para Ouvintes e Surdos, *Int. J. Educ. Teach.*, 2024, **7**(3), 125–142, DOI: 10.31692/2595-2498.v7i3.396.
42 J. M. S. Ferraz, M. C. S. Velozo, D. D. Da Silva, C. A. Da Silva Júnior and A. M. T. A. De Figueirêdo, Química Verde e a Metáfora Da Bipirâmide Triangular (MBT): Uma Avaliação Dos Cinco Níveis de Representação Da Química Em Uma Proposta Pedagógica Inclusiva, *Int. J. Educ. Teach.*, 2025, **8**(1), 1–21, DOI: 10.31692/2595-2498.v8i1.255.
43 A. Perosa, F. Gonella and S. Spagnolo, Systems Thinking: Adopting an Emergy Perspective as a Tool for Teaching Green Chemistry, *J. Chem. Educ.*, 2019, **96**(12), 2784–2793, DOI: 10.1021/acs.jchemed.9b00377.
44 K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. Mackellar and J. E. Wissinger, Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability, *J. Chem. Educ.*, 2019, **96**(12), 2872–2880, DOI: 10.1021/acs.jchemed.9b00354.
45 K. M. D. Reyes, K. Bruce and S. Shetranjiwalla, Green Chemistry, Life Cycle Assessment, and Systems Thinking: an Integrated Comparative-Complementary Chemical Decision-Making Approach, *J. Chem. Educ.*, 2023, **100**(1), 209–220, DOI: 10.1021/acs.jchemed.2c00647.
46 M. K. Orgill, S. York and J. Mackellar, Introduction to Systems Thinking for the Chemistry Education Community, *J. Chem. Educ.*, 2019, **96**(12), 2720–2729, DOI: 10.1021/acs.jchemed.9b00169.
47 V. Talanquer and A. R. Szozda, An Educational Framework for Teaching Chemistry Using a Systems Thinking

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Approach, *J. Chem. Educ.*, 2024, **101**(5), 1785–1792, DOI: 10.1021/acs.jchemed.4c00216.
48 C. A. Da Silva Júnior, Triangular Bipyramid Metaphor (TBM), an Imagetic Representation for the Awareness of Inclusion in Chemical Education (ICE), *Braz. J. Dev.*, 2023, **9**(3), 10567–10578, DOI: 10.34117/bjdv9n3-112.
49 J. G. G. Queiroz, J. M. Martins, J. R. G. Lopes, A. S. Jacinto and C. A. Da Silva Júnior, Formação de Professores e Inclusão: Metáfora Da Bipirâmide Triangular No Planejamento de Aulas Inclusivas de Química Para Ouvintes e Surdos, *Int. J. Educ. Teach.*, 2024, **7**(3), 125–142, DOI: 10.31692/2595-2498.v7i3.396.
50 D. D. Da Silva, J. M. S. Ferraz, M. C. S. Velozo, J. L. de. C. Campos, N. S. de. Souza, A. M. T. A. D. Figueirêdo and C. A. Da Silva Júnior, Abordagem Inclusiva Da Química Verde e Sustentável Para Estudantes Surdos e Ouvintes No Ensino Médio Integrado, *Cad. Pedagóg.*, 2025, **22**(1), e13065, DOI: 10.54033/cadpedv22n1-008.
51 N. S. de. Souza, A. M. T. A. de. Figueirêdo, C. A. Da Silva Júnior, J. M. S. Ferraz and M. J. F. Tavares, Inclusive Teaching in Organic Chemistry: A Visual Approach in the Time of COVID-19 for Deaf Students, *Int. J. Innov. Educ. Res.*, 2022, **10**(1), 290–306, DOI: 10.31686/ijier.vol10.iss1.3618.
52 M. A. Moreira, *Teorias Da Aprendizagem*, LTC, Rio de Janeiro, 3rd edn, 2023.
53 E. F. S. Masini and M. A. Moreira, *Aprendizagem Significativa Na Escola*, CRV, Curitiba, 1st edn, 2017.
54 M. A. Moreira, *Ensino e Aprendizagem Significativa*, Editora Livraria da Física, São Paulo, 1st edn, 2017.
55 S. E. Toulmin, *Os Usos Do Argumento*, Martins Fontes, São Paulo, 3rd edn, 2022.
56 L. P. Sá, A. C. Kasseboehmer and S. L. Queiroz, Esquema de Argumento de Toulmin Como Instrumento de Ensino: Explorando Possibilidades, *Ens. Pesqui. Educ. Ciênc.*, 2014, **16**(3), 147–170, DOI: 10.1590/1983-21172014160307.
57 N. K. Obhi, J. Moir, A. Oseolorun and A. S. Cannon, The Journey towards an Inclusive Green Chemistry Education Community of Practice by Prioritizing Diversity, Equity, Belonging, and Respect for an Open-Access Online Platform, *Sustain. Chem. Pharm.*, 2025, **44**, 101944, DOI: 10.1016/j.scp.2025.101944.
58 M. C. S. Velozo, J. M. S. Ferraz, J. L. da. C. Campos, N. S. De Souza, C. A. Da Silva Júnior and A. M. T. A. De Figueirêdo, Metáfora Da Bipirâmide Triangular (MBT): Uma Sequência Didática Desenvolvida a Partir Dos Cinco Níveis de Representações Da Química, *Cuad. educ. desarro.*, 2024, **16**(1), 1340–1363, DOI: 10.55905/cuadv16n1-070.
59 J. M. Martins and C. A. Da Silva Júnior, A Tabela Periódica Da Química Verde e Sustentável (TPQVS) Em Libras Como Recurso Didático e Interdisciplinar Para Surdos, *Rev. Espaço*, 2025, 136–150, DOI: 10.20395/revesp.2025.63.1.136-150.
60 G. Bakan and M. A. Bircan, Enhancing 21st Century Skills of Primary School Students in Rural Areas through STEM Activities, *J. Educ. Res.*, 2025, 1–16, DOI: 10.1080/00220671.2025.2517265.
61 M. B. Goris, I. Silva Lopes, G. Verschoor, J. Behagel and M. I. V. Botelho, Popular Education, Youth and Peasant Agroecology in Brazil, *J. Rural Stud.*, 2021, **87**, 12–22, DOI: 10.1016/j.jrurstud.2021.08.003.
62 E. Dobbelaar, S. S. Goher, J. L. Vidal, N. K. Obhi, B. M. B. Felisilda, Y. S. L. Choo, H. Ismail, H. L. Lee, V. Nascimento, R. Al Bakain, M. Ranasinghe, B. L. Davids, A. Naim, N. Offiong, J. Borges and T. John, Towards a Sustainable Future: Challenges and Opportunities for Early-Career Chemists, *Angew. Chem., Int. Ed.*, 2024, **63**, e202319892, DOI: 10.1002/anie.202319892.
63 A. S. Cannon, J. C. Warner, J. L. Vidal, N. J. O'Neil, M. M. S. Nyansa, N. K. Obhi and J. W. Moir, A Promise to a Sustainable Future: 10 Years of the Green Chemistry Commitment at Beyond Benign, *Green Chem.*, 2024, **26**(12), 6983–6993, DOI: 10.1039/D4GC00575A.
64 D. Henderson and K. Morgan, Rural Innovation and the Green Transition: The Role of Further Education Colleges, *J. Rural Stud.*, 2025, **114**, 103565, DOI: 10.1016/j.jrurstud.2025.103565.
65 M. Palermo, A. M. Kelly and R. Krakehl, Chemistry Teacher Retention, Migration, and Attrition, *J. Chem. Educ.*, 2021, **98**(12), 3704–3713, DOI: 10.1021/acs.jchemed.1c00888.