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AI-Driven Socio-Scientific Issues Approach in Green Chemistry Education: Effects on Learners' Chemical Literacy and Scientific Argumentation Skills

Efefany Jane H. Jumarito[1,4*] Jethur Faith M. Gampo-an[3] Mary Anne V. Galo[2,4] & Edna B. Nabua[4]

[1]JH Cerilles State College, Mati, San Miguel, Zamboanga del Sur, Philippines

[2]Central Mindanao University, Maramag, Bukidnon, Philippines

[3]Department of Education, Division of Zamboanga del Sur, Philippines

[4]Mindanao State University – Illigan Institute of Technology, Illigan, Philippines

***Corresponding**

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ABSTRACT

Artificial intelligence (AI) has demonstrated considerable potential in enhancing educational practices, while the integration of socio-scientific issues (SSI) in science instruction provides meaningful learning experiences that promote higher-order thinking and societal responsibility. This study examined the effects of an AI-mediated instructional approach integrating Socio-Scientific Issues within Green Chemistry Education (AI-SSI in GCE) on learners' chemical literacy (CL) and scientific argumentation skills (SAS). A one-group pretest–posttest quasi-experimental design was employed involving 31 Grade 11 learners. Data were collected using a Hydrocarbons Chemical Literacy Test (H-CLT), a 30-item multiple-choice instrument aligned with established chemical literacy domains, and a Claim–Evidence–Reasoning–based Argumentative Writing Assessment (CER-AWA). The results revealed statistically significant improvements with large effect sizes in both chemical literacy and scientific argumentation skills following the intervention. Learners demonstrated enhanced abilities to apply chemical knowledge across content, contextual, higher-order, and affective domains, particularly in addressing real-world environmental issues such as plastic pollution. Analysis of scientific argumentation indicated that learners were able to construct complete claims, select relevant evidence, and partially articulate coherent scientific reasoning linking evidence to claims. Additionally, learners exhibited increased awareness of green chemistry principles, environmental sustainability, and the societal implications of chemical decision-making. In conclusion, the AI-SSI in GCE instructional approach effectively fostered cognitive, argumentative, green chemistry awareness, and socio-affective learning outcomes. The findings support the integration of socio-scientific issues and green chemistry concepts into chemistry instruction and highlight the potential of AI as a pedagogical scaffold. However, ethical considerations related to AI use in education may be addressed, and continued optimization and professional dialogue among educators are essential to ensure responsible and learner-centered implementation.

Key Words: Ai-Driven Instruction, Integrated Socio-Scientific Issue, Green Chemistry Education, Chemical Literacy, Scientific Argumentation Skill, Claim-Evidence-Reason Framework

INTRODUCTION

In recent decades, escalating environmental challenges have intensified global concern and prompted critical reflection across scientific disciplines (Morales et al., 2024). In response, industrial chemistry has undergone a paradigmatic shift toward the design of chemical products and processes that prioritize human health and environmental sustainability (Cannon et al., 2023). Parallel to this transformation, science education has increasingly aligned its curricular goals with principles of environmental education, emphasizing sustainability as a core learning outcome. Chemistry education, in particular, has entered a continuous process of "environmentalization," wherein environmental considerations are systematically integrated into chemical knowledge and practice (Sjöström et al., 2016). Central to this movement is green chemistry, which promotes the design of chemical products and processes that minimize or eliminate the use and generation of hazardous substances (Manahan, 2005). The integration of green chemistry into chemistry education has thus been recognized as a crucial step in preparing students to address contemporary environmental challenges and contribute to a sustainable future (Mitarlis et al., 2023).

Embedding green chemistry principles within science education equips teachers with the pedagogical and conceptual tools necessary to foster sustainable practices in the classroom while inspiring the next generation of scientists and engineers. These future professionals are expected not only to possess strong disciplinary knowledge but also to critically evaluate and act upon complex socio-scientific issues. Sjöström et al. (2016) emphasized that the philosophy of green chemistry education must be expanded beyond technical problem-solving to incorporate socio-critical perspectives. Such an approach supports the development of informed citizens and professionals who can comprehend global complexity, engage in value-laden decision-making, and actively participate in democratic processes related to sustainability and environmental governance.

As scientific, industrial, and environmental systems become increasingly intertwined, students must be prepared to engage with dilemmas arising at the intersection of science, society, and ethics. This necessity underscores the importance of developing substantial scientific knowledge alongside the skills required to address complex, real-world problems (Vogelzang, 2020). Students must also acquire competencies that enable meaningful participation in democratic decision-making processes concerning socio-environmental issues (Sjöström et al., 2016). Consequently, the growing complexity of contemporary society demands the advancement of students' scientific literacy. Scientific literacy is broadly defined as the ability to apply scientific knowledge, identify investigable questions, and draw evidence-based conclusions to understand natural phenomena and make informed decisions about human-induced changes in the environment (MM, R. Y., et al., 2020).

Within science education, chemical literacy represents a key dimension of scientific literacy. Chemical literacy refers to an individual's understanding of chemical concepts—including particulate matter, chemical reactions, laws, theories, and their applications in everyday life (Fahmina et al., 2019). Shwartz et al. (2006) conceptualized chemical literacy as comprising four interrelated domains: (1) chemical content knowledge, (2) chemistry in context, (3) higher-order learning skills, and (4) affective aspects toward chemistry, as further elaborated by Sjöström et al. (2024). Learning chemistry poses significant challenges for students, as it requires the integration of macroscopic, submicroscopic, and symbolic representations to construct coherent conceptual understanding (Rahmawati et al., 2024). Students who demonstrate strong chemical literacy are able to explain everyday phenomena using chemical principles, solve problems based on chemical reasoning, and apply chemical knowledge to real-life contexts (Pardiana, 2024). Moreover, chemically literate individuals value chemical knowledge and can meaningfully apply it in their daily lives (Arbid et al., 2020).

Higher-order learning skills are essential to the development of chemical literacy. These include the ability to formulate meaningful questions, seek relevant information, evaluate evidence, and construct reasoned explanations (Novitasari et al., 2022; Anggraini & Wahyuni, 2020). Fadly (2022) further asserted that chemical literacy entails competence in explaining scientific phenomena, evaluating and designing scientific investigations, and interpreting scientific data and evidence. These competencies align closely with the goals of contemporary chemistry education, particularly in addressing environmentally relevant and socially situated chemical issues.

In this educational landscape, socioscientific issues (SSIs) have gained prominence as an instructional approach that inherently connects scientific concepts with societal relevance (Johnson et al., 2020). SSI-based instruction emphasizes scientific argumentation as a central practice, fostering deep conceptual understanding while addressing ethical, social, and environmental dimensions of scientific problems (Kolong et al., 2024). Argumentation involves the construction and communication of reasoned claims supported by evidence and logical justification, enabling learners to engage in critical dialogue and decision-making (Jho & Ha, 2024).

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Osborne (2010) highlighted that effective argumentation requires the ability to evaluate competing claims, consider counterarguments, and weigh alternative lines of reasoning. Through argumentation, students actively reconcile prior knowledge with new evidence, thereby enhancing scientific reasoning and critical thinking skills. Such skills are transferable to everyday problem-solving and decision-making related to socioscientific issues (Alindara & Ana, 2018).

To support the development of scientific argumentation, McNeill and Krajcik (2008) proposed the Claim–Evidence–Reasoning (CER) framework, which structures students' arguments into three components: a claim that answers a scientific question, evidence consisting of relevant data, and reasoning that links the evidence to the claim using scientific principles. The CER framework has been widely recognized for its effectiveness in scaffolding students' argumentation, particularly within SSI contexts. Empirical evidence, such as the study by Istiana and Herawati (2019), demonstrates a significant relationship between students' argumentation skills and their capacity to solve environmental problems, underscoring the instructional value of structured argumentation in science education.

Despite the acknowledged benefits of SSI-based instruction and argumentation frameworks, engaging students in higher-order reasoning remains a persistent challenge. Effective scaffolding is essential to support learners as they progress toward more sophisticated forms of reasoning (Quintana, 2004). Technology-enhanced embedded scaffolding offers timely and adaptive support that facilitates deep conceptual understanding and the development of higher-order cognitive skills (Kaldaras et al., 2024). In particular, artificial intelligence (AI) has emerged as a promising tool for providing adaptive scaffolding that supports learners' reasoning, reflection, and knowledge construction (Roll et al., 2018). Zhai et al. (2024) reported that AI-based tools can scaffold students' engagement with socioscientific issues by guiding evidence evaluation and ethical reasoning. However, needs assessments indicate that many science teachers and students remain unfamiliar with SSI pedagogy, resulting in limited classroom implementation (Kolong et al., 2022). Furthermore, SSI-based instruction is often perceived as demanding in terms of content mastery, pedagogical expertise, and instructional time (Pitiporntapin et al., 2016).

Although existing research has explored green chemistry education, SSI-based instruction, scientific argumentation, chemical literacy, and AI-supported learning independently, studies that systematically integrate these components within a unified instructional framework remain limited, particularly at the senior high school level. Moreover, empirical investigations examining the use of AI as a scaffolding tool to support SSI-based green chemistry instruction and the development of chemical literacy are scarce. Many prior studies focus primarily on general scientific literacy or conceptual understanding, with fewer explicitly addressing chemical literacy across its four domains within environmentally relevant topics such as plastic pollution.

In response to these gaps, the present study seeks to immerse Grade 11 learners in an AI-driven instructional framework grounded in a Socio-Scientific Issues approach to Green Chemistry Education (AI-SSI in GCE). This approach aims to enhance students' chemical literacy and scientific argumentation skills in relation to key chemistry competencies involving hydrocarbons, plastic polymers, and plastic pollution. Specifically, this study aims to:

(1) determine the levels of Grade 11 learners' chemical literacy and scientific argumentation skills before and after exposure to the AI-SSI in GCE; and

(2) examine the significant differences in learners' chemical literacy and scientific argumentation skills following participation in the AI-SSI in GCE intervention.

MATERIALS AND METHODS

The study adopted a quasi-experimental research design, specifically a one-group pretest–posttest design complemented by qualitative support. A single experimental group was exposed to the AI-SSI instructional intervention in Green Chemistry Education. Learners' chemical literacy related to hydrocarbons and their scientific argumentation skills were measured before and after the intervention to determine changes attributable

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to the instructional treatment. This design was selected to allow for the examination of learning gains within an authentic classroom setting where random assignment was not feasible.

The research participants consisted of Grade 11 STEM learners enrolled in a public senior high school in Zamboanga del Sur. A total of 31 learners participated in the study, selected through convenience sampling, as all participants had completed the relevant chemistry curriculum components required for the intervention. The sample comprised 45% female and 55% male learners. Convenience sampling was deemed appropriate given the exploratory nature of the study and the accessibility of participants within the instructional context.

Prior to the implementation of the intervention, formal permission to conduct the study was secured from the school principal, and the class adviser was informed of the research objectives and procedures. Learners were invited to participate voluntarily, and informed consent was obtained. Of the 43 students enrolled in the class, 31 consented to participate and were included in the study. Before the commencement of the instructional treatment, participants were administered a Hydrocarbons Chemical Literacy Test (H-CLT) and a Claim–Evidence–Reasoning–based Argumentative Writing Assessment (CER-AWA). These pretests were used to establish baseline levels of chemical literacy across its sub-domains and scientific argumentation skills prior to exposure to the AI-SSI in GCE intervention.

Following the pretest administration, the instructional treatment was implemented. The AI-SSI in GCE intervention employed a socioscientific issue–based approach centered on plastic pollution, integrating green chemistry principles into the teaching of hydrocarbons and polymer-related concepts. An AI-based tool was incorporated as an instructional scaffold to support learners in constructing, evaluating, and refining scientific arguments during learning activities. This approach was designed to promote meaningful engagement with environmental issues while strengthening learners’ chemical understanding and argumentation competencies.

After the completion of the intervention, posttests were administered using the same instruments: the Hydrocarbons Chemical Literacy Test (H-CLT) and the CER-based Argumentative Writing Assessment (CER-AWA). The posttest data were collected to evaluate the effectiveness of the AI-SSI in GCE instruction in enhancing learners’ chemical literacy and scientific argumentation skills. Comparative analysis of pretest and posttest results was conducted to determine learning gains associated with the intervention.

Teaching Intervention

The teaching intervention was implemented over seven instructional sessions, each lasting 45 minutes. The lessons addressed four interconnected chemistry topics: hydrocarbons and their reactions, polymers and polymerization, bioplastics and conventional plastics, and introductory green chemistry concepts. The intervention was anchored in a Socio-Scientific Issues (SSI) approach integrated with Green Chemistry principles, emphasizing the global challenge of plastic pollution and the exploration of plant-based plastics as sustainable alternatives to single-use conventional plastics. Specifically, the intervention incorporated selected Green Chemistry Principles, including waste prevention (Principle 1) through careful calculation of reactant inputs and outputs; less hazardous chemical syntheses (Principle 3); the use of safer solvents and chemicals (Principle 5); the use of renewable feedstocks (Principle 7); and the design of chemicals and products that degrade after use (Principle 10), exemplified by biodegradable plastics.

SSI Pedagogy Component. The lesson flow follows the *identification of social issues, exploration of scientific content, evaluation of evidence, argumentation and reflection*. These five (5) steps are where the whole lessons revolved.

I. Identification of social issue. Identification of social issues is the foundation of the lesson as this is used as guide in accomplishing the general objective (Jumarito & Nabua, 2024), i.e., the enhancement of chemical literacy and argumentation skill, the integration of green chemistry concepts to promote sustainability, the use of AI to scaffold and offers personalized feedback and learning among learners, to be conscious of the problems in the community and to exercise and contribute to a solution.

The lesson began by asking learners about social issues they've observed in the community. Problems related to personal; family, environment, economy and health were identified. The teacher facilitates which is the most important and most realistic to contribute to a solution. After that, the learners are in consensus to single out the most pressing problem of their community which is plastic pollution. Following the discussion is the documentary video clips presentation highlighting both local (Philippines) and global impacts of plastic waste. Guided questions were provided to activate students' prior knowledge and prompt initial reflections on the causes, consequences, and possible solutions to plastic pollution. The central SSI question given was, "How should society address the environmental impacts of plastics, considering the scientific properties of conventional plastics, bioplastics, and the limitations of each?", was presented to frame the issue as an open-ended problem requiring scientific and societal consideration.

II. Exploration of scientific content. This part aims to provide a scientific foundation for informed reasoning, explicit instruction on relevant chemistry concepts was conducted. This included discussions on hydrocarbons, fossil fuel origins, polymer structures, degradation lifetimes, and the mechanisms of addition polymerization (initiation, propagation, and termination), and green chemistry concepts. These concepts are salient for students to understand the chemical structure, properties, production of conventional plastics and bioplastics and their implications for environmental persistence and sustainability.

III. Evaluation of evidence. In this part of the lesson, the class worked in small group and followed by hands-on experiment on bioplastic production through a plant-based feedstock. Then the learners evaluate and test the bioplastic materials. Properties, like flexibility, tensile, durability and degradation in a short time was also assessed by the learners. Through this, the learners critically analyze the functional performance and limitations of bioplastics, providing evidence to support or challenge claims regarding their viability as alternatives to conventional plastics within the socioscientific context.

IV. Argumentation. In this activity, students were given the opportunity to debate with an Artificial Intelligence tool using 'sidekick from school AI', through an AI-assisted Claim–Evidence–Reasoning (CER) debate activity. Learners' construct their claims regarding the promotion of bioplastics in the Philippines, then supported these claims with scientific evidence both from class discussion, laboratory experiment, google search and local context, and justified their reasoning. The AI system will just challenge the learners' arguments by providing counterclaims and alternative perspectives, prompting rebuttals and deeper evaluation of evidence. Specifically, the strong points of this activity are: i) promote deeper engagement with scientific evidence, as AI can consistently generate well-structured and evidence-based counterclaims; ii) ensures equal access to argumentation practice, as every learners receives direct engagement and feedback; iii) encourages self-regulated learning, as learners can easily analyze why their argument was being challenged and how to improve them. The teacher just acts as a facilitator, entertaining students queries, monitoring learners' activity, observing and documenting learners' engagement.

This activity is well supported by authors like Guo et al., (2023), in the task design the students interacted with an argumentative chatbot named 'Argumate' before engaging in debates with their classmates. During their interaction, the chatbot helped the students to generate ideas for supporting their position and predict opposing viewpoints.

V. Reflection. To extend learning beyond the classroom, learners apply their scientific understanding to real-world contexts by developing policy recommendations to the local government units LGU's regarding plastics use. Through this, learners were more likely to be aware of the issues in the context and propose solutions. This process allows students to develop environmental responsibility and informed decision-making.

Artificial Intelligence (AI) Component. The AI integration functioned as a pedagogical scaffold rather than an autonomous instructor. Specifically, the AI was used to (1) prompt learners to articulate claims related to socio-scientific issues, (2) guide students in identifying relevant chemical evidence, and (3) encourage justification through scientific principles aligned with green chemistry concepts. The AI provided adaptive, rule-based feedback by detecting missing components of the Claim–Evidence–Reasoning (CER) structure and offering guiding questions (e.g., "Which chemical principle supports this claim?") rather than direct answers. Feedback was intentionally non-evaluative and reflective, designed to promote metacognitive engagement and learner autonomy. Ethical safeguards were implemented to ensure responsible AI use. The teacher informed the learners that AI served as a learning aid and not an authoritative source. There were no personal data stored, and all interactions were conducted within teachers' supervision. Furthermore, teacher oversight was maintained throughout the intervention to validate accuracy and prevent overreliance on AI-generated responses.

Data Collection Tools

Two primary instruments were used for data collection. The first was the Hydrocarbons Chemical Literacy Test (H-CLT), a 30-item multiple-choice assessment covering hydrocarbons and their reactions, polymers and polymerization, bioplastics and conventional plastics, and introductory green chemistry concepts, followed by one argumentation item. The test was developed in alignment with Shwartz et al.'s chemical literacy framework and distributed across four subdomains: scientific and content knowledge (Items 1, 2, 3, 4, 7, 9, 10, 14); chemistry in context (Items 8, 11, 12, 13, 15, 18, 19, 22); higher-order learning skills (Items 5, 6, 16, 17, 20, 21, 23, 24, 26, 27, 30); and affective aspects (Items 25, 28, 29).

The second instrument was the Claim–Evidence–Reasoning–based Argumentative Writing Assessment (CER-AWA). This assessment consisted of a single socioscientific issue–based question designed to elicit learners' chemical understanding within environmental and societal contexts and to assess their ability to construct coherent arguments using the CER framework.

Data Analysis Techniques

Descriptive statistics, including means, percentiles, and standard deviations, were computed using the Statistical Package for the Social Sciences (SPSS) to determine learners' levels of chemical literacy and scientific argumentation. To examine significant differences between pretest and posttest scores, the Wilcoxon Signed Rank Test was employed due to the non-normal distribution of the data. The assumptions for this nonparametric test were verified using the Shapiro–Wilk test, which indicated skewed distributions for both the H-CLT and CER-AWA scores ($p < 0.05$). All statistical analyses were conducted at a 0.05 level of significance.

RESULTS AND DISCUSSIONS

This section presents and discusses the findings of the study in relation to the research objectives outlined in the preceding sections. The discussion integrates the empirical results with relevant theoretical perspectives and prior research to elucidate their implications for the teaching and learning of chemistry, particularly within the context of Artificial Intelligence– driven Socio-Scientific Issues (AI-SSI) approach in Green Chemistry Education.

Learners' level of Chemical Literacy before and after the exposure of the AI-SSI approach in GCE instruction

Chemical literacy encompasses learners' capacities to understand and explain chemical phenomena using precise scientific language; to read, write, and critically evaluate chemical information; to communicate ideas effectively; and to apply chemical concepts in informed decision-making (Cigdemoglu et al., 2017). Within this study, learners' chemical literacy was operationalized and assessed using a 30-item multiple-choice instrument aligned with the four subdomains proposed by Shwartz et al. (2006): scientific and chemical content knowledge, chemistry in context, higher-order learning skills, and affective aspects. Learners' responses were interpreted according to established categorical descriptors to determine their levels of chemical literacy.

To examine changes in chemical literacy attributable to the AI-SSI approach in Green Chemistry Education, pretest and posttest mean percentage scores were computed and compared. Table 1 presents the learners' mean percentage scores in chemical literacy related to hydrocarbons before and after the instructional intervention. The results provide an empirical basis for evaluating the extent to which exposure to the AI-SSI instructional framework influenced learners' chemical understanding across the identified subdomains.

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Table 1. Learners' Level of Hydrocarbons Chemical Literacy during Pre and Post-intervention

	Pre-Intervention		**Post-Intervention**	
Domains of Chemical Literacy	**Mean Percentage Score**	**Interpretation**	**Mean Percentage Score**	**Interpretation**
A. Scientific and Content Knowledge (SCK)	67.92%	Functional Chemical Literacy	68.33%	Functional Chemical Literacy
B. Chemistry in Context (CC)	68.33%	Functional Chemical Literacy	76.67%	Conceptual Chemical Literacy
C. Higher Order Skills (HOS)	83.03%	Conceptual Chemical Literacy	87.88%	Multidimensional Chemical Literacy
D. Affective Aspect (AA)	92.22%	Multidimensional Chemical Literacy	95.56%	Multidimensional Chemical Literacy
Overall Chemical Literacy (CL)	76.00%	Conceptual Chemical Literacy	85.66%	Multidimensional Chemical Literacy

There are four (4) domains of chemical literacy according to Schwartz et al. (2006) framework namely: A. Scientific and Content Knowledge (SCK); B. Chemistry in Context (CC); C. Higher Order Skills (HOS); D. Affective Aspect (AA). It can be seen that all of the domains have an improvement after the intervention.

Specifically, science content knowledge which was used to assess learners' understanding of polymers, hydrocarbons, and plastic materials have a very slight improvement after the intervention and still falls to *"functional chemical literacy"* (68.33%). Based on literature, functional literacy is a higher level than nominal literacy. At this level, students can describe concepts correctly, but still have limited understanding. Students knew the concept but had not clearly understood what was meant by the problem, so that in answering the question students still experienced difficulties and led to errors in providing the answers (Fahmina et al. 2019; Shwartz et al., 2006). This is similar to the study of Fahmina et al. (2019) in which they claimed that the ability of students at the functional literacy level was still low.

Chemistry in Context (CC) which was assessed through socio-scientific scenarios that require learners to interpret chemical concepts like addition and condensation reactions of polymer, refining processes of polymers, etc within environmental and societal situations have improved to *"conceptual chemical literacy"* (76.67%). This means that students' literacy includes understanding of the main conceptual schemes of a material and then linking the scheme to a general understanding of chemistry. In addition, conceptual literacy also includes procedural understanding and the understanding of the investigation process or inclusion (Shwartz et al., 2006). Specifically, learners conceptually understand chemistry as applied to tourism and fisheries affected by plastic waste; local packaging company redesigning materials; LGU decision on bioplastic subsidies; and food vs bioplastic crop competition.

Higher Order Skills (HOS) which was measured through analysis and evaluation level test items and are further examined through CER-based arguments have further improved from "conceptual chemical literacy" to "multidimentional chemical literacy" (87.88%). The multi-dimensional literacy level is the highest level in the ability of chemical literacy. At this level, the ability of students is drawn up to not only understand the concept of chemistry but also combine scientific inquiry procedures. Here, students also develop an understanding of the material concepts with the application of science and technology in their daily lives (Fahmina et al. 2019; Shwartz, 2006). More specifically, students make connections with various disciplines, between science,

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technology and society. With the ability of chemical literacy at the multi-dimensional literacy level, students are expected to be able to solve the problems that arise in social life. Specifically, the result suggests that the intervention successfully supported learners in the development of higher order skills.

The Affective Aspect (AA) which was captured through learners' perceptions, values, and attitudes toward sustainable chemistry and environmental responsibility was also in "multidimentional chemical literacy" (95.56%). Specifically, learners' economic considerations in bioplastics, responsible polymer use, and environmental responsibility in chemistry are already at a high level even before the introduction of the treatment. The further increase in post-intervention suggests that the instructional approach not only supported cognitive gains but also strengthened learners' engagement and value orientation toward chemistry.

The overall Chemical Literacy (CL) demonstrated a positive progression from "conceptual chemical literacy" to "multidimentional chemical literacy". This suggests that the intervention reflects a holistic impact to learners chemical literacy in concepts like hydrocarbons, polymers, socio-scientific issues, and Green Chemistry. As Shwartz et al. (2006) exclaimed, the perspectives of multidimensional chemical literacy incorporates an understanding of science that extends beyond the concepts of scientific disciplines and procedures of scientific investigation. In this context, AI driven SSI approach in GCE instruction as the utilized intervention in this study, effectively contributed in enhancing learners' chemical literacy in becoming individuals capable of engaging with chemistry-related issues in informed and meaningful ways. The result of the study is in consonance to Novitasari (2022) in which the development of chemistry emodule based on SSI is effective to enhance students' chemical literacy.

Figure 1 below presents the data in a more concrete and comprehensive way through a bar graph. It can be seen that all domains have gradually increased after the treatment. SCK has the smallest increase, no significant difference in the pretest-posttest score. However, a similar study has found out that SSI-based chemistry interventions show improvements in application, reasoning, and literacy, but do not always produce large increases in raw content knowledge because they engage learners in context and argumentation rather than direct content memorization (Fadly, 2022).

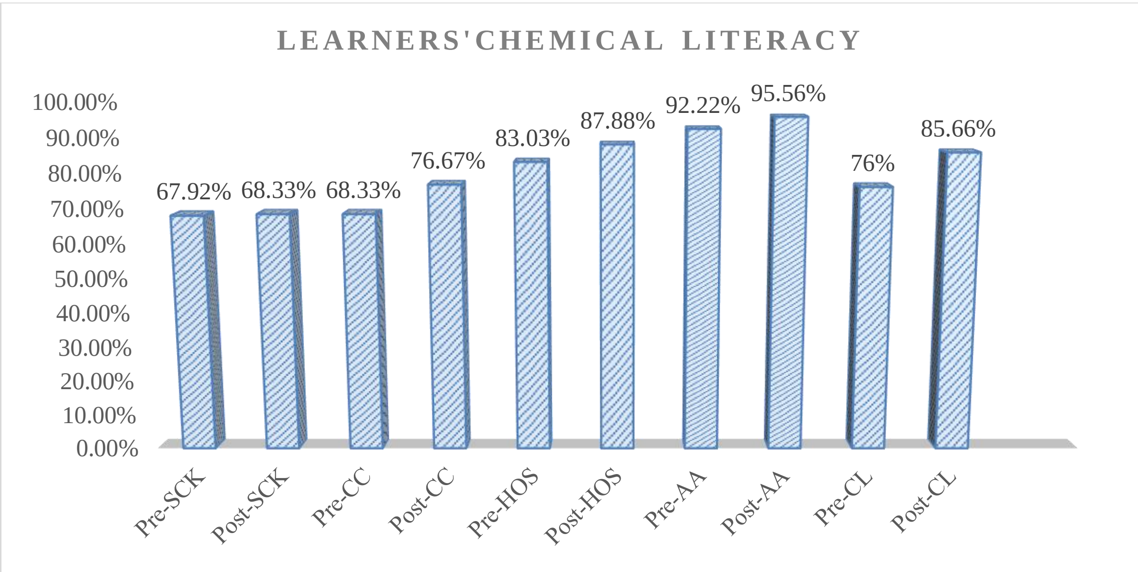

Figure 1. Learners' Chemical Literacy on Hydrocarbons in specifics to 4 Domains

Moreover, Wiyarsi et al. (2021) claimed that chemical literacy includes content knowledge, but that teaching strategies often emphasize broader aspects (context, reasoning, affect) which can lead to larger gains in those domains while content increases are less dramatic. Meanwhile, context and higher order skills have clearly increased after the treatment, which largely contributes to the progression of the overall chemical literacy from conceptual to multidimensional level.

Learners' level of Argumentation Skill before and after the exposure of the AI-SSI approach in GCE instruction

Scientific argumentation constitutes a central practice in science learning, as it enables learners to construct, justify, and critique claims using evidence-based reasoning, thereby promoting critical thinking and informed decision-making (Zesen & Osman, 2025). In this study, learners' scientific argumentation skills were assessed using the Claim–Evidence–Reasoning (CER) framework proposed by McNeill and Krajcik (2008). This framework operationalizes argumentation through three core components: the formulation of a scientifically valid claim, the selection of relevant and sufficient evidence, and the articulation of coherent reasoning that logically connects evidence to the claim.

Learners' written responses to socioscientific argumentation tasks were evaluated using a rubric adapted from McNeill and Krajcik (2008). The rubric assessed the accuracy and clarity of claims, the appropriateness and sufficiency of evidence, and the coherence and scientific validity of the reasoning provided. Pretest and posttest scores were analyzed to determine changes in learners' argumentation performance following exposure to the AI-SSI instructional intervention in Green Chemistry Education.

Table 2. Learners' Scientific Argumentation Skill during Pre and Post-intervention

Condition	Mean Score	Standard Deviation	Interpretation
Pre-Argumentation Skill	4.6452	0.60819	*Developing Proficiency*
Post-Argumentation Skill	5.3358	0.96470	*Developing Proficiency*

Table 2 presents the descriptive statistics for learners' performance on the Claim–Evidence–Reasoning–based Argumentative Writing Assessment (CER-AWA). As shown, learners' pre-intervention scientific argumentation skills clustered around a mean score of 4.65, which was interpreted as developing proficiency. Following exposure to the AI-SSI instructional intervention in Green Chemistry Education particularly the integration of socioscientific discussions on plastic pollution and AI-assisted debate activities, learners' mean posttest score increased to 5.34 (SD = 0.96). Although the post-intervention performance remained within the developing proficiency category, the observed increase in mean score indicates a positive shift in learners' argumentation skills.

Notably, the higher standard deviation observed in the posttest suggests increased variability in learners' argumentation performance. This pattern indicates that while a number of learners demonstrated substantial improvement in constructing scientific arguments, others exhibited more gradual progress. Such variability is pedagogically meaningful, as it reflects differential responsiveness to SSI-based and AI-supported instructional scaffolds rather than uniform or superficial gains. Learners at the developing proficiency level were generally able to formulate accurate and largely complete claims, provide most of the relevant evidence to support their positions, and demonstrate partial understanding of scientific concepts in explaining how the evidence supports the claim (McNeill & Krajcik, 2008). However, limitations remained in fully addressing the research question and in articulating comprehensive, conceptually robust reasoning.

The observed improvements in scientific argumentation align with prior research emphasizing the role of SSI-based instruction and structured argumentation frameworks in fostering learners' reasoning abilities. The AI-assisted debate component, in particular, appears to have contributed to learners' increased engagement with counterarguments and evidence evaluation, thereby supporting incremental advancement in argumentation proficiency.

Significant difference of Grade 11 learners' Level of Chemical Literacy

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To determine whether the observed changes in learners' chemical literacy were statistically significant, a nonparametric analysis was conducted using the Wilcoxon Signed Rank Test for related samples. This test was deemed appropriate given the non-normal distribution of the data. Table 3 presents the SPSS output summarizing the test statistics and significance values for learners' chemical literacy scores before and after the intervention.

Table 3. Test Significant Difference in the Chemical Literacy Scores of Grade 11 Learners

Domains of Chemical Literacy	Pretest (MPS)	Posttest (MPS)	p-value	Interpretation	r-value	Interpretation
A. Scientific and Content Knowledge (SCK)	67.92%	68.33%	0.975	Not Significant	0.0056	Negligible Effect Size
B. Chemistry in Context (CC)	68.33%	76.67%	0.067	Not Significant	0.329	Medium Effect Size
C. Higher Order Skills (HOS)	83.03%	87.88%	0.083	Not Significant	0.311	Medium Effect Size
D. Affective Aspect (AA)	92.22%	95.56%	0.408	Not Significant	0.149	Small Effect Size
Overall Chemical Literacy (CL)	**76.00%**	**85.66%**	**0.000**	**Highly Significant**	**0.638**	**Large Effect Size**

At the 95% confidence level, the results indicate a statistically significant difference between learners' pretest and posttest chemical literacy scores ($p < 0.001$), accompanied by a large effect size ($r = 0.638$). This finding demonstrates that the implementation of the AI-driven Socio-Scientific Issues (SSI) approach in Green Chemistry Education exerted a substantial impact on learners' overall chemical literacy related to hydrocarbon concepts. The magnitude of the effect suggests that the intervention was not only statistically effective but also educationally meaningful in enhancing learners' capacity to engage with chemistry in informed and applied ways.

A domain-specific analysis, however, reveals a more nuanced pattern of outcomes. For the Scientific and Content Knowledge (SCK) domain, the mean percentage score exhibited only a marginal increase, with no statistically significant difference between pretest and posttest results ($p = 0.975$) and a negligible effect size ($r = 0.006$). This outcome indicates minimal change in learners' foundational chemistry content knowledge, reinforcing the view that SSI-oriented instruction may not primarily target decontextualized factual acquisition.

Similarly, the Chemistry in Context (CC) domain showed a slight increase in mean percentage scores. Although this change did not reach statistical significance ($p = 0.067$), the associated medium effect size ($r = 0.329$) suggests a practically meaningful improvement in learners' ability to relate hydrocarbon concepts to plastic materials and real-world environmental contexts. This result underscores the value of context-rich instruction in promoting transferable chemical understanding, even when statistical thresholds are not met.

The Higher-Order Skills (HOS) domain also demonstrated a modest increase in mean scores, with the Wilcoxon test indicating no statistically significant difference ($p = 0.083$) but yielding a medium effect size ($r = 0.311$). This finding reflects a substantial practical impact of the intervention on learners' analytical, evaluative, and reasoning skills, which are central to chemical literacy at higher levels. These outcomes align with the intended goals of the AI-SSI approach, which emphasizes argumentation, evidence evaluation, and decision-making over rote memorization.

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In the Affective Aspect (AA) domain, learners likewise exhibited an increase in post-intervention scores. However, this change was neither statistically significant ($p = 0.408$) nor associated with a large effect size ($r = 0.149$). The relatively small effect suggests that learners' attitudes, values, and environmental awareness regarding sustainable chemistry were already well developed prior to the intervention, leaving limited room for measurable growth. This finding is consistent with Herman (2015), who reported that SSI-based contexts tend to heighten students' environmental awareness, particularly when baseline concern is initially low.

Although not all individual domains of chemical literacy demonstrated statistically significant pretest–posttest differences, the intervention produced a robust and statistically significant enhancement in overall chemical literacy, as evidenced by the large effect size. These results suggest that domains such as chemistry in context and higher-order skills contributed disproportionately to the overall learning gains, resulting in a meaningful progression toward multidimensional chemical literacy. This pattern is supported by prior studies indicating that SSI-based approaches effectively enhance chemical literacy by situating chemical knowledge within socially relevant and authentic contexts (Fadly et al., 2022; Stuckey et al., 2013; Childs et al., 2015). Moreover, Novitasari et al. (2022) reported a strong relationship between chemical literacy development and SSI-based learning framed around real-world social problems grounded in scientific contexts.

Significant difference of Grade 11 learners' Level of Scientific Argumentation Skill

To determine whether the observed changes in learners' scientific argumentation skills were statistically significant, pre-intervention and post-intervention scores from the Claim–Evidence–Reasoning–based Argumentative Writing Assessment (CER-AWA) were analyzed using the Wilcoxon Signed Rank Test for related samples. This nonparametric test was selected due to the non-normal distribution of the data. Table 4 presents the Wilcoxon test results obtained from the SPSS analysis, indicating the significance levels associated with changes in learners' scientific argumentation skills following the AI-SSI instructional intervention.

Table 4. Test Significant Difference in the Argumentation Scores of Grade 12 Learners

	Pretest ($\bar{x}$)	**Posttest ($\bar{x}$)**	**p-value**	**Interpretation**	**r- value**	**Interpretation**
Respondents (n=31)	4.6452 *Developing Proficiency*	5.3358 *Developing Proficiency*	0.003	Significant	0.5415	Large Effect size

At the 95% confidence level, the results reveal a statistically significant difference between learners' pretest and posttest scientific argumentation scores ($p < 0.001$), accompanied by a large effect size ($r = 0.542$). This finding indicates that the implementation of the AI-driven Socio-Scientific Issues (SSI) approach in Green Chemistry Education exerted a substantial effect on enhancing learners' scientific argumentation skills, particularly in relation to hydrocarbon concepts as applied to plastic polymers and the contemporary issue of plastic pollution. The magnitude of the effect underscores the instructional value of integrating AI-supported argumentation within socioscientific contexts to promote evidence-based reasoning and decision-making.

The integration of artificial intelligence in this study transformed how learners engaged with, processed, and applied chemical knowledge related to conventional plastics and bioplastics. Through AI-supported interactions, learners accessed adaptive scaffolding that aligned with their individual levels of argumentation proficiency and learning pace, while receiving immediate and targeted feedback. Such personalized learning opportunities facilitated deeper engagement with scientific evidence and reasoning. These findings are consistent with Bugaje (2024), who reported that AI-enhanced chemistry instruction fosters more interactive, engaging, and efficient learning experiences. Similarly, Yuriev et al. (2025) noted that generative AI tools are increasingly employed as instructional supplements, enabling students to draft, evaluate, and critique ideas while maintaining instructor oversight. In this context, AI served to augment, rather than replace traditional instruction, reinforcing its pedagogical legitimacy in contemporary science classrooms.

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Within the framework of socioscientific issues, prior research has demonstrated that engagement with SSI contexts promotes the development of scientific literacy skills, including argumentation, critical thinking, ethical reasoning, and moral judgment (Herman, 2015). SSI-based learning requires learners to grapple with controversial and complex real-world problems, compelling them to integrate multiple perspectives, evaluate competing evidence, and propose informed solutions (Fadly et al., 2022; Rahayu, 2017). The findings of the present study suggest that the strategic integration of AI within SSI-based green chemistry instruction further amplifies these learning processes, resulting in meaningful gains in both chemical literacy and scientific argumentation. Consistent with prior work, instructional approaches that combine socioscientific issues with structured scientific writing and reasoning frameworks have been shown to significantly improve students' argumentation skills and academic achievement.

CONCLUSION AND RECOMMENDATION

The findings of this study demonstrate that AI-driven instruction grounded in a Socio-Scientific Issues approach to Green Chemistry Education (AI-SSI in GCE) effectively enhanced Grade 11 learners' chemical literacy and scientific argumentation skills related to hydrocarbon concepts, plastic polymers, and plastic pollution. Beyond cognitive gains, learners also developed heightened awareness of green chemistry principles, environmental sustainability, and the societal dimensions of chemical decision-making.

Although improvements in specific domains of chemical literacy were not uniformly statistically significant, this outcome should not be interpreted as a limitation. Rather, it reflects the inherently gradual and cumulative nature of literacy development. The substantial gains observed in contextual understanding and higher-order reasoning underscore the importance of embedding chemistry instruction within authentic, socially relevant problems. These findings imply that chemistry teachers should more frequently integrate socioscientific issues into instruction and actively engage learners in evidence-based decision-making processes grounded in scientific knowledge.

Furthermore, while AI-driven instruction proved effective in promoting learner outcomes, its ethical and pedagogical implications warrant careful consideration. Issues related to data privacy, academic integrity, and equitable access must be addressed to ensure responsible implementation. Continuous refinement and evidence-based evaluation of AI-supported teaching practices are therefore essential. Ongoing professional dialogue and research among educators are recommended to optimize AI integration in ways that are ethical, effective, and centered on meaningful student learning.

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REFERENCES

1. Alindra, A. L., & Ana, A. (2018). Argumentation and reasoning skills in socioscientific issues. Innovation of Vocational Technology Education, 14(2), 44. https://doi.org/10.17509/invotec.v14i2.14356
2. Anggraini, S. D., & Wahyuni, D. (2020). Science Textbook Based on Socio-Scientific Issues (Ssi) For Environmental Pollution to Increase Student Science Literacy in Junior High School. Journal of Physics: Conference Series, 1563(1), 12053. Iop Publishing.
3. Arbid, El, Samir, Sara, & Tairab, Hassan H. (2020). Science Teachers' Views About Inclusion of Socio-Scientific Issues in Uae Science Curriculum and Teaching. International Journal of Instruction, 13(2), 733–748.

4. Bugaje, B. M. (2025). Innovative Teaching Strategies for Future Development of Chemistry Education in Nigeria. Kashere Journal of Education, 7(1), 2008–217. Retrieved from https://www.ajol.info/index.php/kje/article/view/292997
5. Cannon, A.S.; Anderson, K.R.; Enright, M.C.; Kleinsasser, D.G.; Klotz, A.R.; Neil, N.J.O.; Tucker, L.J. (2023). Green Chemistry Teacher Professional Development in New York State High Schools: A Model for Advancing Green Chemistry. J. Chem. Educ, 100, 2224–2232. [CrossRef]
6. Celik, S. (2014). Chemical literacy levels of science and mathematics teacher candidates. Australian Journal of Teacher Education, 39(1), Article 1. https://doi.org/10.14221/ajte.2014v39n1.1
7. Childs, P. E., Hayes, S., & O'Dwyer, A. (2015). Chemistry and everyday life: relating secondary school chemistry to the current and future lives of students. Rotterdam: Sense.
8. Cigdemoglu, C., & Geban, O. (2015). Improving students' chemical literacy levels on thermochemical and thermodynamics concepts through a context-based approach. Chemistry Education Research and Practice, 16(2), 302–317. https://doi.org/10.1039/C5RP00007F
9. Fadly, D., Rahayu, S., Dasna, I. W., & Yahmin, Y. (2022). The effectiveness of a SOIE strategy using socio-scientific issues on students' chemical literacy. International Journal of Instruction, 15(1), 237–258. Retrieved from https://e-iji.net/ats/index.php/pub/article/view/444
10. Fahmina, S. S., Indriyanti, N. Y., Setyowati, W. A. E., Masykuri, M., & Yamtinah, S. (2019). Dimension of chemical literacy and its influence in chemistry learning. IOP Conference Series: Journal of Physics: Conference Series, 1233, 012026. https://doi.org/10.1088/1742-6596/1233/1/012026
11. Guo, K., Zhong, Y., Li, D., & Chu, S. K. W. (2023). Effects of chatbot-assisted in-class debates on students' argumentation skills and task motivation. Computers & Education, 203, 104862. https://doi.org/10.1016/j.compedu.2023.104862
12. Hazen, R. M., & Trefil, J. S. (1991). Achieving chemical literacy. Journal of Chemical Education, 68(5), 392–394. https://doi.org/10.1021/ed068p392
13. Istiana, R., & Herawati, D. (2019). Student argumentation skill analysis of socioscientific issues in solving environmental problems.
14. Jho, H., & Ha, M. (2024). Towards effective argumentation: Design and implementation of a generative AI-based evaluation and feedback system. Journal of Baltic Science Education, 23(2), 280–291. https://doi.org/10.33225/jbse/24.23.280
15. Johnson, J., Macalalag, A.Z. & Dunphy, J. Incorporating socioscientific issues into a STEM education course: exploring teacher use of argumentation in SSI and plans for classroom implementation. Discip Interdscip Sci Educ Res **2**, 9 (2020). https://doi.org/10.1186/s43031-020-00026-3
16. Jumarito, E., & Nabua, E. (2024). Integrating Indigenous practices in chemistry instructional material for a culturally responsive STEM curriculum. Asia Research Network Journal of Education, 4(1), 1–15. Retrieved from https://so05.tci-thaijo.org/index.php/arnje/article/view/268476
17. Kaldaras, L., Wang, K. D., Nardo, J. E., Price, A., Perkins, K., Wieman, C., & Salehi, S. (2024). Employing technology-enhanced feedback and scaffolding to support the development of deep science understanding using computer simulations. International Journal of STEM Education, 11, Article 30.
18. Kolong, A. I, Hairulla M. S, & Pitiporntapin S. (2022). Science teachers and students' perspectives on SSI-based instruction: Basis on the development of SSI-based curricular resources. Thabiea: Journal of Natural Science Teaching, 6(1), 1–24. http://dx.doi.org/10.21043/ thabiea.v6i1.18215
19. Kolong, A. I., Salic-Hairulla, M., & Pitiporntapin, S. (2025). Enhancing students' argumentation skills using Socioscientific Issue (SSI)-based teaching in the respiratory system topic. Kasetsart Journal of Social Sciences, 46(2), Article 460216. https://doi.org/10.34044/j.kjss.2025.46.2.16
20. Manahan, S. E. (2005). Green chemistry and the ten principles of designing safer chemical processes. CRC Press.
21. McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. https://eric.ed.gov/?id=EJ733792
22. McNeill, K. L., & Krajcik, J. (2008). Inquiry and scientific explanations: Helping students use evidence and reasoning. In J. Luft, R. Bell & J. Gess-Newsome (Eds.), Science as Inquiry in the Secondary Setting (pp. 121–134). National Science Teachers Association Press.
23. Mitarlis, M., Azizah, U., & Yonata, B. (2023). The integration of green chemistry principles in basic chemistry learning to support achievement of Sustainable Development Goals (SDGs) through education. Journal of Technology and Science Education, 13(1), 233. https://doi.org/10.3926/jotse.1892

24. Novitasari, R., Waluyo, J., & Nuriman, N. (2022). Chemistry e-module based on Socio Scientific Issues (SSI) for reaction rate material to increase senior high school students' chemical literacy. Eduvest - Journal of Universal Studies, 2(9), 1811–1816. https://doi.org/10.59188/eduvest.v2i9.588
25. Osborne, J. (2010). Arguing to learn in science: The role of argumentation in developing scientific literacy. Science, 328(5977), 463–466. https://doi.org/10.1126/science.1183944
26. Pardiana. (2024). Research trends in chemical literacy: A systematic literature review from 2013 to 2022. Journal of Research in Mathematics, Science, and Technology Education, 1(1), 12–18
27. Pitiporntapin S., Yutakom N., & Sadler T. D. (2016). Thai pre-service science teachers' struggles in using Socio-scientific Issues (SSIs') during practicum. Asia-Pacific Forum on Science Learning and Teaching, 17(2). https://eric.ed.gov/?id=EJ1145733
28. Quintana, C. (2004). A scaffolding framework for supporting the development of problem-solving expertise in complex domains. Journal of the Learning Sciences, 13(3), 337–372. https://doi.org/10.1207/s15327809jls1303_2
29. Rahayu, S. (2017). Promoting The 21st Century Scientific Literacy Skills through Innovative Chemistry Instruction. AIP Conference Proceedings, Yogyakarta, Indonesia.
30. Rahmawati, Y., Erdawati, E., Ridwan, A., Veronica, N., & Hadiana, D. (2024, February 15). Developing students' chemical literacy through the integration of dilemma stories into a STEAM project on petroleum topic. Rahmawati | Journal of Technology and Science Education. https://www.jotse.org/index.php/jotse/article/view/2221/822?
31. Roll, I., Russell, D. M., & Gašević, D. (2018). Learning at scale. International Journal of Artificial Intelligence in Education, 28(4), 471–477. https://doi.org/10.1007/s40593-018-0170-7
32. Shwartz, Y., Ben-Zvi, R., & Hofstein, A. (2006). Chemical literacy: What does this mean to scientists and school teachers? Journal of Chemical Education, 83(10), 1493–1499. https://doi.org/10.1021/ed083p1493
33. Sjöström, J., Yavuzkaya, M., Guerrero, G., & Eilks, I. (2016). Environmentalization of chemistry education: Integrating sustainability and socio-critical perspectives. Journal of Chemical Education, 93(8), 1355–1365. https://doi.org/10.1021/acs.jchemed.6b00345
34. Sjöström, J., Eilks, I. & Zuin, V.G. Towards Eco-reflexive Science Education. Sci & Educ **25**, 321–341 (2016). https://doi.org/10.1007/s11191-016-9818-6
35. Sjöström, J., Yavuzkaya, M., Guerrero, G., & Eilks, I. (2024). Critical chemical literacy as a main goal of chemistry education aiming for climate empowerment and agency. Journal of Chemical Education, 101(10), 4189–4195. https://doi.org/10.1021/acs.jchemed.4c00452
36. Stuckey, M., Hofstein, A., Mamlok-Naaman, R., & Eilks, I. (2013). The meaning of 'relevance' in science education and its implications for the science curriculum. Studies in Science Education, 49(1), 1–34. https://doi.org/10.1080/03057267.2013.802463
37. Vogelzang, J., Admiraal, W. F., & van Driel, J. H. (2020). Effects of Scrum methodology on students' critical scientific literacy: The case of Green Chemistry. Chemistry Education Research and Practice, 21(3), 940–952. https://doi.org/10.1039/D0RP00066C
38. Wiyarsi, A., Prodjosantoso, A. K., & Nugraheni, A. R. E. (2021a). Promoting students' scientific habits of mind and chemical literacy using the context of Socio-Scientific issues on the inquiry learning. Frontiers in Education, 6. https://doi.org/10.3389/feduc.2021.660495
39. Yuriev, E., Orgill, M., & Holme, T. A. (2025). Generative AI in chemistry education: Current progress, pedagogical values, and the challenge of rapid evolution. Journal of Chemical Education, 102(9), 3773–3776. https://doi.org/10.1021/acs.jchemed.5c01105
40. Zesen, T., & Osman, K. (2025). Enhancing scientific argumentation skills in the classroom: Strategies for fostering critical thinking in science education. Foro de Educación, 23(1), 270–288.
41. Zhai, X., Chu, X., Chai, C. S., Jong, M. S. Y., Istenic, A., Spector, M., Liu, J.-B., Yuan, J., & Li, Y. (2021). A review of artificial intelligence (AI) in education from 2010 to 2020. Complexity, 2021, Article 8812542. https://doi.org/10.1155/2021/8812542