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Development of a Citizen Science–Based Thermochemistry Module Oriented toward Scientific Literacy and Environmental Awareness

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Abstract: *This study aimed to develop and evaluate a Citizen Science–based thermochemistry teaching module as an innovative learning resource in senior high school chemistry. The study employed a research and development design using the ADDIE model, encompassing analysis, design, development, implementation, and evaluation stages. The participants were 119 eleventh-grade students from a public senior high school in Gorontalo. Data were collected through expert validation, teacher and student practicality questionnaires, scientific literacy tests, and environmental awareness questionnaires. The results indicated that the developed module achieved high validity and practicality and demonstrated effective learning outcomes, as reflected in improved scientific literacy and increased levels of environmental awareness after implementation. The novelty of this study lies in the integration of the Citizen Science approach into a thermochemistry module that explicitly connects abstract energy concepts with authentic environmental exploration activities, an area that has been rarely addressed in chemistry education research. These findings suggest that the developed module is feasible and pedagogically meaningful for supporting scientific literacy and environmental awareness in senior high school chemistry learning.*

Keywords: *Citizen Science; teaching module; thermochemistry; scientific literacy; environmental awareness*

INTRODUCTION

Thermochemistry is widely perceived as one of the most challenging topics in chemistry learning due to its abstract concepts and the need to link microscopic energy changes with macroscopic and real-life phenomena. Preliminary findings at SMA Negeri 2 Gorontalo City revealed that students' scientific literacy reached only 45%, which falls into the low category. This condition indicates students' limited ability to interpret energy-related phenomena in daily life, such as enthalpy changes in combustion processes or heat transfer occurring in the surrounding environment. Low scientific literacy is also reflected in students' limited environmental awareness, as shown by their minimal participation in school-based environmental programs, including plastic waste reduction, waste banks, and reforestation activities (Ibrahim & Sutiani, 2025).

This local condition is consistent with broader national and international data. According to the Ministry of Education and Culture (2024), more than half of Indonesian senior high school students are categorized as having low scientific literacy, particularly in environmental context indicators and data-based problem-solving skills. Similarly, PISA 2025 reported that Indonesian students experience difficulties in applying energy concepts to analyze environmental issues such as household energy consumption, air pollution, and the thermal impacts of combustion processes. These findings indicate a persistent gap between science learning practices in schools and the demands of 21st-century competencies, which emphasize scientific reasoning and environmental literacy (Sari, 2024).

One contributing factor to this problem is the continued dominance of conventional, teacher-centered instruction in thermochemistry learning. Such approaches tend to emphasize formula memorization and algorithmic problem-solving, while providing limited opportunities for students to observe real-world phenomena, conduct investigations, or relate energy concepts to their everyday experiences. As a result, students often remain passive recipients of information and struggle to construct meaningful conceptual understanding of thermochemical processes (Suyanti & Ramadhani, 2022).

In recent years, the Citizen Science approach has emerged as a promising pedagogical strategy that actively engages students as contributors to scientific inquiry through environmental exploration, field data collection, and analysis of authentic phenomena. Studies conducted between 2022 and 2024 have reported that Citizen Science activities can enhance scientific literacy, critical thinking, and environmental awareness by involving learners directly in real scientific practices. However, most existing studies are concentrated in biology and environmental science contexts—such as biodiversity monitoring, water quality assessment, and waste analysis—while applications in chemistry education remain limited (Ballard, 2023).

This situation reveals a clear research gap: the absence of Citizen Science–based learning modules specifically designed for thermochemistry. Despite its strong relevance to environmental issues—such as energy consumption, combustion-related air pollution, and waste incineration—thermochemistry learning rarely integrates direct environmental exploration activities, including temperature measurement, observation of household energy use, or analysis of everyday combustion processes. Consequently, existing instructional materials have not sufficiently supported the development of students' scientific literacy and environmental awareness in a contextual and participatory manner (Az-zahra & Darmana, 2024).

Based on these identified needs and gaps, this study aims to develop and evaluate a Citizen Science–based thermochemistry teaching module for senior high school students. Specifically, the objectives of this study are to:
(1) examine the validity of the developed module based on expert judgment,
(2) assess its practicality from the perspectives of teachers and students, and
(3) evaluate its effectiveness in supporting students' scientific literacy and environmental awareness.
Through this development, the study is expected to contribute an innovative and contextually grounded learning resource that bridges abstract thermochemistry concepts with real-world environmental issues (Ahmad, 2024).

METHODS

This study employed a research and development (R&D) design using the ADDIE development model, which consists of five stages: analysis, design, development, implementation, and evaluation. At the analysis stage, classroom observations, curriculum document analysis, and semi-

structured interviews with chemistry teachers were conducted to identify students' learning difficulties in thermochemistry, particularly in understanding enthalpy changes, endothermic–exothermic reactions, and their connections to environmental phenomena (Batchelder et al., 2023).

During the design stage, a structured Citizen Science–based thermochemistry module was planned, comprising learning objectives, concept maps, contextual learning materials, Citizen Science activity worksheets, simple experimental guidelines, temperature and heat measurement procedures, and environmental reflection sheets. The development stage involved producing the draft module enriched with visual illustrations, infographics, locally relevant environmental examples, and investigative activities that could be implemented in both school and home settings (Tsaniyah et al., 2025).

The implementation stage was conducted with 119 eleventh-grade students from SMA Negeri 2 Kota Gorontalo. The evaluation stage focused on assessing the validity, practicality, and effectiveness of the developed module.

Research Instruments

Data were collected using expert validation sheets, teacher and student practicality questionnaires, a scientific literacy test, and an environmental awareness questionnaire. The expert validation instrument evaluated five aspects: content feasibility, material relevance, presentation, visual design, and language quality. Practicality questionnaires assessed ease of use, clarity of learning procedures, language comprehensibility, and suitability for classroom implementation (Putri & Rahmatih, 2023).

Scientific literacy was measured using a 20-item Higher Order Thinking Skills (HOTS) test developed based on PISA indicators, including the ability to explain scientific phenomena, interpret data and graphs, and evaluate scientific evidence in environmental contexts (Andini & Siswanto, 2025).

Environmental awareness was assessed through a 30-item Likert-scale questionnaire covering three indicators: environmental knowledge, environmental attitudes, and pro-environmental actions (Adawiyah et al., 2022).

Reliability and Data Analysis

Instrument reliability was examined using Cronbach's Alpha coefficient. The scientific literacy test demonstrated high reliability ($\alpha \geq 0.80$), while the environmental awareness questionnaire showed very high reliability ($\alpha \geq 0.85$), indicating good internal consistency (Julien, 2025).

Data were analyzed using descriptive statistics. Module **validity and practicality** were interpreted based on percentage scores and categorized into predefined criteria (very low to very high). The **effectiveness** of the module in improving scientific literacy was determined using normalized gain (N-gain) analysis, with effectiveness levels classified as low, moderate, or high (Zhu & He, 2025).

RESULT AND DISCUSSION

1. Module Validity

he validity of the Citizen Science–based thermochemistry module was evaluated through expert judgment covering five aspects: content

Tabel 1 Teaching Module Validation Result

Validation Aspects	Presentation (%)	Category
Content Eligibility	92,0	Very Valid
Material Suitability	89,0	Very Valid
Presentation	91,0	Very Valid
Visual Display	90,0	Very Valid
Linguistics	92,0	Very Valid
Average	**90,7**	**Very Valid**

The results of expert validation indicate that the Citizen Science–based thermochemistry module achieved an overall

validity score of 90.7%, which falls within the *very valid* category according to established instructional material evaluation criteria. This finding demonstrates that the module meets essential standards in terms of content accuracy, pedagogical coherence, and instructional design. High validity is a critical prerequisite for further implementation, as it ensures that the developed product is conceptually sound and aligned with curriculum demands before being tested for practicality and effectiveness (Araújo et al., 2022) .

From a content perspective, the high score reflects the module's success in accurately presenting core thermochemistry concepts, particularly those related to enthalpy changes, exothermic–endothermic reactions, and energy transfer. More importantly, these concepts are contextualized through real environmental phenomena, such as waste combustion and temperature changes in the surrounding environment. This contextual integration strengthens conceptual relevance and supports scientific literacy development, which emphasizes understanding science as it operates in real-world contexts rather than as abstract knowledge (Finger et al., 2023).

The presentation structure also received a very high evaluation, indicating that the learning flow was logically organized and consistent with the Citizen Science inquiry cycle. Activities were arranged sequentially—from observation and data collection to analysis and conclusion—allowing students to engage in scientific practices systematically. Such structuring is essential for inquiry-based learning, as it scaffolds students' thinking processes and reduces cognitive overload during complex learning tasks (Lestarani, 2022).

In terms of visual design and language use, validators highlighted that the module's layout, illustrations, and graphical elements supported readability and student engagement. Clear visuals and concise language help students focus on conceptual understanding rather than decoding text, which is particularly important in thermochemistry, a topic often perceived as abstract and mathematically demanding. The consistent formatting and use of scientific terminology further reinforce the module's academic quality (Ballard, 2023).

Overall, the high validity scores across all assessed aspects indicate strong internal consistency between content, pedagogy, and design. This suggests that the module is theoretically grounded and pedagogically appropriate, making it suitable for classroom trials. These findings align with previous studies emphasizing that well-validated instructional materials are more likely to produce meaningful learning outcomes when implemented in real educational settings (Pratama et al., 2025).

2. Practicality of Teaching Modules

The practicality evaluation of the module provides insight into its feasibility when used by teachers and students in authentic classroom contexts. Teacher responses yielded a practicality score of **89.65%**, categorized as *very practical*, indicating that the module can be implemented without significant obstacles. This suggests that the instructional design aligns well with classroom realities, including time allocation, availability of tools, and assessment demands.

Teachers emphasized that the clarity of instructions and the structured sequence of activities facilitated lesson implementation. The use of simple experimental procedures and easily accessible materials reduced logistical barriers, allowing teachers to focus on guiding inquiry rather than managing technical difficulties. This finding is significant because instructional innovations often fail not due to theoretical weaknesses but due to practical constraints in real classrooms.

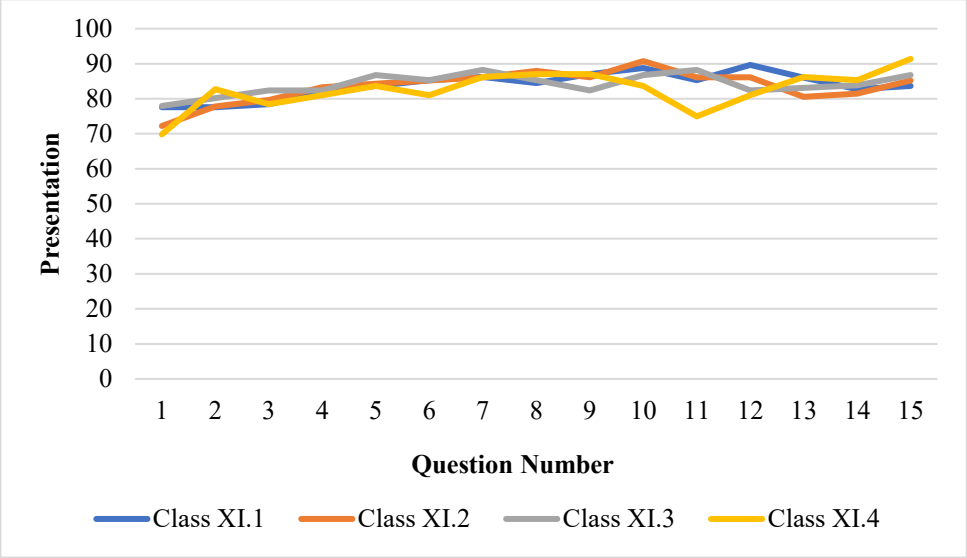

Figure 1 Level of Practicality of Teaching Modules According to Students

Student responses resulted in a practicality score of **77.58%**, which falls into the *practical* category. Rather than merely indicating ease of use, this score reflects students' perceptions of clarity, engagement, and relevance. Students reported that hands-on activities, data collection, and environmental observation tasks helped them better understand thermochemistry concepts that were previously considered difficult (Berndt & Nitz, 2023).

Analysis of student performance distribution across question indicators shows relatively stable achievement patterns among classes. This stability suggests that the module supports equitable learning opportunities, reducing disparities that often arise from differences in prior knowledge or classroom dynamics. Importantly, minor fluctuations in specific items highlight areas requiring additional instructional support, particularly for higher-order analytical tasks (Wibowo, 2021).

Overall, the practicality findings indicate that the module is not only usable but also adaptable to diverse classroom conditions. These results underscore that Citizen Science–based learning materials can be realistically integrated into formal education settings when instructional design considers both pedagogical intent and classroom constraints.

3. Effectiveness of Scientific Literacy

a. Improved Scientific Literacy

The effectiveness of the module was examined through improvements in students' scientific literacy, measured using pretest–posttest scores and normalized gain (N-gain) analysis. The observed increase from a mean pretest score of **45** to a posttest score of **82**, with an N-gain value of **0.70**, indicates a *high level of effectiveness*. This finding suggests that the module substantially enhanced students' ability to engage with scientific concepts and practices.

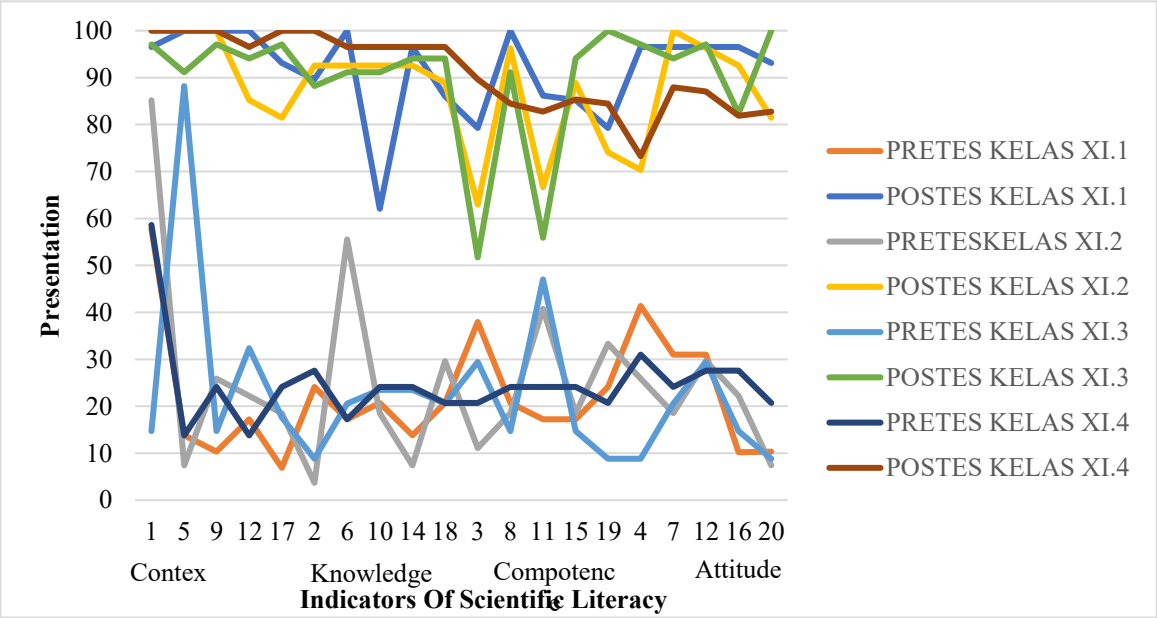

Figure 2 Scientific Literacy Skills According to Students

Beyond numerical improvement, a more meaningful interpretation lies in the pattern of gains across scientific literacy indicators. Students showed the strongest improvement in explaining scientific phenomena, particularly when interpreting energy changes resulting from environmental processes such as combustion. This indicates that contextual learning experiences supported students in connecting theoretical concepts with observable phenomena.

Improvements in data interpretation and graph analysis further suggest that repeated exposure to empirical measurements and data processing during Citizen Science activities strengthened analytical skills. These competencies are central to scientific literacy, as they enable students to make evidence-based conclusions rather than relying on memorized information.

However, gains related to evaluating scientific evidence were relatively lower compared to other indicators. This suggests that critical evaluation skills may require longer-term and repeated inquiry experiences. The finding aligns with previous research indicating that higher-order reasoning develops gradually and benefits from sustained instructional support.

Taken together, these results demonstrate that the module effectively promotes multiple dimensions of scientific literacy. The consistent improvement across classes indicates that the observed effects are attributable to the instructional design rather than isolated classroom factors.

B. Increased Environmental Awareness

The implementation of the module also resulted in a notable increase in students' environmental awareness, shifting overall scores from moderate to high and very high categories. This improvement reflects not only cognitive understanding but also affective engagement with environmental issues. Students reported greater awareness of the consequences of waste burning, energy consumption, and everyday behaviors that impact the environment.

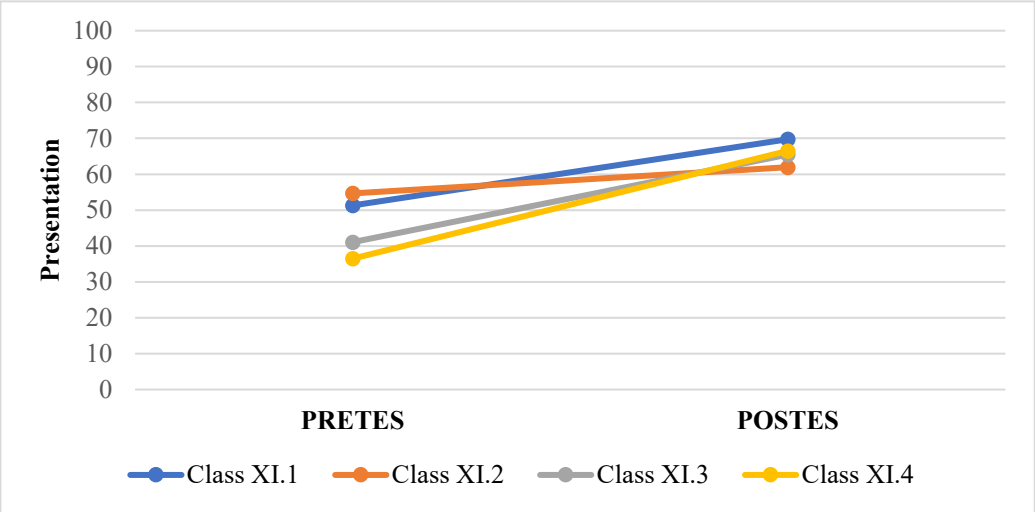

Figure 3 Percentage of Environmental Awareness According to Students

Differences in the magnitude of improvement among classes highlight the complexity of measuring affective outcomes. For instance, classes with higher initial awareness levels exhibited smaller visible gains due to a ceiling effect. This phenomenon does not indicate a lack of impact but rather a limitation in detecting subtle changes when baseline scores are already high.

Additionally, variations in classroom interaction and participation during Citizen Science activities may have influenced outcomes. Classes that engaged more actively in discussion, reflection, and collaborative investigation tended to show stronger improvements. This finding reinforces the idea that affective learning outcomes are closely linked to social interaction and reflective processes.

Importantly, all classes achieved high posttest scores, demonstrating the module's consistent effectiveness in fostering environmental awareness. Students' direct involvement in observing and analyzing environmental phenomena appears to have strengthened their sense of responsibility and relevance of scientific knowledge.

Overall, the results indicate that integrating environmental investigation into thermochemistry learning can effectively support the development of environmental awareness. This outcome complements cognitive gains in scientific literacy and highlights the holistic impact of the instructional approach.

Analytical Reflection and Reserch Limitations

While the findings demonstrate positive outcomes, it is important to acknowledge several limitations that may influence interpretation. First, the study was conducted in a single institutional context, which may limit the generalizability of the results to other schools with different characteristics.

Second, environmental awareness was measured using self-report questionnaires, which may be influenced by social desirability bias. Although the instrument demonstrated high reliability, self-reported data may not fully capture actual behavioral change in real-life settings (Celestino, 2023).

Third, the study focused on short-term learning outcomes following module implementation. Long-term retention of scientific literacy skills and sustained environmental behavior were not examined, leaving room for future longitudinal studies.

Despite these limitations, the study provides strong initial evidence that Citizen Science–based thermochemistry modules can effectively support both cognitive and

affective learning outcomes. The findings contribute to the growing body of research advocating for contextual, participatory approaches in science education.

Future research should expand implementation across diverse educational contexts, incorporate observational measures of behavior, and examine long-term impacts to strengthen empirical justification and broaden applicability.

CONCLUSION

This study concludes that the developed Citizen Science–based thermochemistry module meets essential quality criteria for learning materials, namely validity, practicality, and effectiveness in senior high school chemistry instruction. The validation results confirm that the module is conceptually accurate, pedagogically coherent, and contextually relevant, particularly in integrating thermochemistry concepts with real environmental phenomena. These qualities indicate that the module is academically sound and suitable for classroom implementation.

From a practical perspective, the module was perceived as feasible and user-friendly by both teachers and students. Clear activity procedures, accessible experimental tasks, and contextual learning experiences enabled smooth implementation across different classroom conditions. This finding highlights that the integration of Citizen Science principles into formal chemistry instruction can be realistically achieved without imposing excessive instructional or logistical demands.

In terms of learning outcomes, the module effectively supported the development of students' scientific literacy, especially in explaining scientific phenomena, interpreting empirical data, and applying thermochemistry concepts to environmental contexts. The inquiry-based and participatory nature of Citizen Science activities allowed students to engage actively in scientific practices rather than passively receiving information, thereby strengthening meaningful learning.

Beyond cognitive outcomes, the module also contributed to the enhancement of students' environmental awareness. Direct involvement in observing, measuring, and reflecting on environmental energy-related phenomena fostered students' sense of responsibility toward environmental issues and encouraged pro-environmental attitudes. This demonstrates that chemistry learning can simultaneously address conceptual understanding and affective dimensions when grounded in authentic contexts.

Overall, this study provides empirical evidence that Citizen Science–based instructional modules represent a promising approach for bridging abstract thermochemistry concepts with real-world environmental issues. The findings contribute to chemistry education research by offering a pedagogically meaningful model that supports scientific literacy and environmental education in alignment with 21st-century learning goals. Future studies are recommended to explore long-term impacts, broader implementation contexts, and behavioral indicators to further strengthen the applicability of this approach.

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