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Analysis of Students' Understanding About Education for Sustainable Development in Green Chemistry-Based Organic Chemistry Laboratory Innovations in The Digital Era

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A B S T R A C T

Education for Sustainable Development (ESD) is essential for promoting sustainability-oriented learning in chemistry education. This study aimed to analyze chemistry education students' understanding, perceptions, and learning needs regarding the integration of ESD in Green Chemistry-based organic chemistry laboratory learning in the digital era. A descriptive survey was conducted with 134 chemistry education students using a validated five-point Likert-scale questionnaire distributed through Google Form. Data were analyzed descriptively using mean scores and percentages. The results showed that students' understanding of ESD was moderate (mean = 3.00; 60%), while their perceptions of Green Chemistry implementation (mean = 3.30; 66%), sustainability relevance (mean = 4.00; 80%), sustainability understanding (mean = 3.70; 74%), and digital innovation (mean = 4.15; 83%) were positive. Students also expressed a very high need for additional ESD-related learning materials (mean = 4.25; 85%). The findings provide empirical evidence of a gap between students' positive perceptions of sustainability-oriented laboratory learning and their conceptual understanding of ESD, suggesting that engagement in sustainability-oriented laboratory practices does not automatically translate into a comprehensive understanding of ESD concepts. Therefore, chemistry educators and curriculum developers should strengthen the integration of ESD concepts through digital resources and explicit instructional strategies in organic chemistry laboratory education.

1. Introduction

The current educational landscape requires learning systems that support innovation and the development of 21st-century skills, including analytical thinking, research competence, problem-solving, critical thinking, and collaboration (Sa-ngiemjit et al., 2025; Volosa et al., 2025). Rapid technological advancement has increased the

need for education to be more flexible, adaptive, and relevant to contemporary contexts (Sari et al., 2025). As a result, education in the digital era must continuously adapt to changing demands while promoting sustainable learning practices (Saputra et al., 2026). Digital technology has also created opportunities to improve the quality of STEM education, with digital literacy playing an important role in enhancing students' understanding of chemistry and supporting academic achievement (Wilczek et al., 2022; Dyantyi-gwanya et al., 2025).

In the context of developing 21st-century skills and utilizing digital technology, chemistry learning needs to be designed in a more contextual manner, including through laboratory activities. Laboratory work plays an important role in chemistry education by enabling students to develop conceptual understanding and experimental skills through direct experience (Kotuľáková et al., 2026). Chemistry education should also provide opportunities for students to apply scientific concepts in meaningful contexts (Munawwarah & Side, 2025). Since chemical concepts are abstract, hierarchical, and interconnected, difficulties in understanding fundamental concepts may hinder meaningful learning and the development of more advanced knowledge (Amelia et al., 2026). In response to these challenges, teacher education needs to strengthen the integration of Education for Sustainable Development (ESD), which aims to prepare individuals to contribute actively and responsibly to a sustainable future while supporting the achievement of the Sustainable Development Goals (SDGs) (Goller & Markert, 2025; Araneo, 2024).

Green Chemistry is an approach that seeks to redesign chemical products and processes to minimize negative impacts on the environment and human health (Utami & Louse, 2026). Integrating Green Chemistry into the curriculum is important for helping students develop a sense of environmental responsibility and make informed decisions about sustainable practices (Araripe & Zeidler, 2024). Green Chemistry education also supports the development of the knowledge, skills, values, and attitudes needed for a sustainable future while helping students relate chemical concepts to their effects on the environment and human health, making learning more meaningful and relevant to ESD principles (Akinsemolu & Onyeaka, 2025; Day et al., 2024). Within the context of ESD, Green Chemistry encourages students to connect theoretical knowledge with practical applications and to consider solutions to environmental problems from different perspectives (Wahyu et al., 2025). Technology-based Green Chemistry learning can enhance student engagement, strengthen 21st-century skills, improve understanding of Green Chemistry concepts, and support quality education (Prasetya et al., 2025).

Previous studies have shown that Green Chemistry education positively contributes to students' learning outcomes and environmental awareness. Green Chemistry-based learning not only enhances students' understanding of chemical concepts but also promotes greater environmental responsibility (Basheer et al., 2025). The implementation of Green Chemistry enables students to better understand the role of chemistry in achieving sustainability, making learning experiences more relevant and meaningful (Armstrong et al., 2024). However, research on ESD integration in Green Chemistry-based organic chemistry laboratories remains limited,

particularly in the digital era, despite the potential of digital technologies to enhance students' learning. (Bewota et al., 2026).

Interest in Green Chemistry has increased alongside growing environmental awareness, promoting safer and more sustainable chemical practices (Armstrong et al., 2024; Kaur et al., 2026). Based on twelve principles that emphasize waste reduction, energy efficiency, and the use of safer materials, Green Chemistry is increasingly recognized as an important component of ESD in higher education (Kotuľáková et al., 2026; Zhang et al., 2023; Widyantoro et al., 2025). However, organic chemistry education is often criticized for emphasizing memorization rather than conceptual understanding (Iyamuremye et al., 2025). Although laboratory activities are intended to develop practical and research skills, they frequently focus on reaction outcomes and techniques while giving limited attention to safety and sustainability issues (Demers et al., 2022; Shetranjiwalla & Hu, 2023). In addition, the use of materials and energy is often discussed without considering its broader social, economic, and environmental impacts, highlighting the need to integrate Green Chemistry and ESD principles into organic chemistry laboratory education (Reyes et al., 2023).

Many pre-service teachers still have a limited understanding of Green Chemistry and sustainability despite being introduced to these concepts during their studies (Sumanik et al., 2024). Research has also identified challenges in implementing ESD in higher education and integrating Green Chemistry into chemistry curricula and laboratory activities (Araneo, 2024; Armstrong et al., 2024). Existing Green Chemistry learning approaches are often limited to environmentally friendly experiments, indicating that broader integration of sustainability concepts is still needed (Vaz et al., 2025; Gunbatar et al., 2025; Obhi et al., 2025). In response to these gaps, this study provides baseline information on students' understanding, perceptions, and learning material needs related to the integration of ESD, Green Chemistry, and digital learning support in organic chemistry laboratories (Wilczek et al., 2022; Araneo, 2024; Bewota et al., 2026; Widyantoro et al., 2025). While previous studies have generally examined Green Chemistry, sustainability awareness, or digital learning separately, limited research has explored how these aspects are interconnected in the context of chemistry education students (Araneo, 2024; Gunbatar et al., 2025).

Although previous studies have examined Green Chemistry education, sustainability awareness, and digital learning separately, limited research has investigated students' understanding, perceptions, and learning needs regarding the integration of ESD, Green Chemistry, and digital learning support in organic chemistry laboratory education. Based on this gap, the present study aims to analyze chemistry education students' understanding of ESD in the context of Green Chemistry-based organic chemistry laboratory innovations in the digital era and to identify their perceptions and learning needs concerning the integration of ESD principles, Green Chemistry practices, and digital technologies in laboratory learning. The findings are expected to provide baseline information for the development of more sustainable, contextual, and digitally supported laboratory education.

2. Methodology

This study employed a survey method with a non-experimental descriptive approach aimed at describing phenomena or conditions as they naturally occur through the identification and description of variables within a specific context (Johnson & Christensen, 2014). Data were collected using a structured five-point Likert-scale questionnaire distributed via Google Form to 134 chemistry education students who had completed an organic chemistry laboratory course from three provinces during the even semester of the 2025/2026 academic year. The participants were selected using convenience sampling based on their accessibility and prior experience in organic chemistry laboratory learning.

The research instrument was developed based on the research objectives, focusing on students' understanding of Education for Sustainable Development (ESD), the integration of Green Chemistry principles in organic chemistry laboratory practices, and digital innovation in sustainable chemistry learning. The questionnaire consisted of screening questions and measurement items related to students' perceptions and understanding of ESD-based Green Chemistry laboratory practices. Prior to data collection, the questionnaire underwent content validation through expert judgment involving four validators: two lecturers from the Chemistry Study Program, Faculty of Mathematics and Science Education (FPMIPA), Universitas Pendidikan Indonesia, and two peer reviewers with expertise in chemistry education, namely a chemistry education lecturer and a chemistry teacher. Each item was assessed in terms of relevance, clarity, and alignment with the research objectives using a five-point rating scale.

Validity and reliability of the questionnaire were evaluated to ensure its suitability as a research instrument. Content validity was assessed using Aiken's V coefficient based on expert judgment to evaluate the relevance and alignment of each questionnaire item with the research objectives. Revisions were made according to the validators' suggestions before the final questionnaire was administered. An item was considered valid if it obtained an Aiken's V value of at least 0.71 (Pratiwi et al., 2026). All questionnaire items achieved Aiken's V values above 0.80, indicating high content validity. Reliability was evaluated using Cronbach's Alpha coefficient based on responses from 134 participants to examine the internal consistency of the instrument. The questionnaire was considered reliable when the Cronbach's Alpha value was ≥ 0.70 (Rianto et al., 2024). The obtained Cronbach's Alpha coefficient of 0.71 indicated an acceptable level of internal consistency, suggesting that the instrument was suitable for data collection.

After the validity and reliability evaluation, the finalized questionnaire was distributed online via Google Form, and the collected data were analyzed descriptively to examine students' responses regarding the integration of ESD in Green Chemistry-based organic chemistry laboratory learning. Prior to data collection, participants were informed about the purpose of the study, the procedures involved, and their rights as research participants. Participation was entirely voluntary, and informed consent was obtained before completing the

questionnaire. Respondents' confidentiality and anonymity were ensured, and the collected data were used exclusively for academic research purposes.

Data were then collected using a five-point Likert scale ranging from 1 to 5. The response categories for each item were adjusted to the characteristics being measured, such as level of understanding, frequency, perception, and respondents' needs. These variations represent a flexible Likert-type scale; however, all responses were converted into a uniform numerical scale, where 1 represents the lowest value and 5 represents the highest value (Koo & Yang, 2025). This approach allows the collected data from different questionnaire items to be compared and analyzed consistently. Although the response categories varied depending on the measured aspects, all items were converted into the same numerical scale to support consistent interpretation through descriptive statistical analysis. The Likert scale used as the reference for data interpretation is presented in Table 1.

Table 1. Likert Scale Assessment

Score	Criteria
5	Strongly Agree
4	Agree
3	Neutral
2	Disagree
1	Strongly Disagree

The score categorization was determined by dividing the percentage range (0–100%) into five equal intervals to classify the findings into five levels: very low, low, moderate, high, and very high. This categorization was used to facilitate the interpretation of students' responses by converting percentage scores into descriptive categories. The classification process allows the overall response patterns for each measured aspect to be interpreted more clearly based on the obtained percentage values. Through this approach, the descriptive results can provide a general overview of students' understanding, perceptions, and learning needs related to ESD integration in Green Chemistry-based organic chemistry laboratory practices. The use of percentage-based categories also helps present the findings in a more systematic manner and makes comparisons among different aspects easier. The categorization criteria used for data interpretation are presented in Table 2.

Table 2. Score Categorization

Percentage (%)	Category
0–20	Very Low
21–40	Low
41–60	Moderate
61–80	High
81–100	Very High

The percentage score for each aspect was calculated to determine the level of students' responses based on the obtained scores. The percentage calculation was

performed by comparing the total obtained score with the maximum possible score. The formula used for calculating the percentage score is presented as follows:

$$\text{Percentage} = \frac{\text{Obtained Score}}{\text{Maximum Score}} \times 100\%$$

The research instrument covered several aspects related to students' understanding and perceptions of ESD integration in Green Chemistry-based organic chemistry laboratory practices. The questionnaire items were designed to measure students' understanding of Education for Sustainable Development (ESD), the frequency of Green Chemistry principles implementation in laboratory activities, and students' perceptions regarding the relevance of laboratory practices to sustainability issues. In addition, the instrument included items related to the extent to which Green Chemistry-based laboratory activities improved students' understanding of sustainability principles within the ESD framework. The questionnaire also examined the role of digital innovation, including the use of digital media and online platforms, in supporting students' understanding of Green Chemistry-based laboratory learning in the digital era. The instrument also explored students' needs for additional ESD-related materials in organic chemistry laboratory activities. The aspects and corresponding questionnaire items are presented in Table 3.

Table 3. List of Questionnaire Items

No	Question (Q)
1.	How well do you understand the concept of Education for Sustainable Development (ESD)?
2.	In the organic chemistry laboratory course you have taken, how frequently are Green Chemistry principles integrated?
3.	In your opinion, does the implementation of ESD in Green Chemistry-based organic chemistry laboratory work make the learning experience more relevant to sustainability issues?
4.	To what extent does Green Chemistry-based organic chemistry laboratory work improve your understanding of sustainability principles within Education for Sustainable Development (ESD)?
5.	Do you feel that digital innovations (such as the use of digital media or online platforms) help you understand Green Chemistry-based organic chemistry laboratory work in the digital era?
6.	Do you think there is a need for improvement or additional ESD-related materials in Green Chemistry-based organic chemistry laboratory work?

3. Results and Discussion

In the data collection process, students were asked to provide responses through a questionnaire developed based on several aspects, including laboratory experience, understanding of ESD, implementation of Green Chemistry principles, sustainability relevance, the role of digital technology, and the need for material development. The collected responses were processed to identify students' perceptions and understanding regarding the integration of ESD in Green Chemistry-based organic chemistry laboratory practices. The data analysis involved calculating the mean scores and percentages for each aspect measured in

the questionnaire. The obtained percentage values were then interpreted using the predetermined categorization criteria to provide a clearer description of the findings. This analysis was conducted to identify the overall response patterns and describe the level of students' understanding and perceptions related to sustainable chemistry learning. The detailed results of the analysis for each measured aspect are presented in Table 4.

Table 4. Research Findings

Aspect	Mean	Percentage	Category
Understanding of ESD	3.00	60%	Moderate
Implementation of Green Chemistry principles	3.30	66%	High
Relevance to sustainability issues	4.00	80%	High
Improvement in understanding	3.70	74%	High
Role of digital innovation	4.15	83%	Very High
Need for material development	4.25	85%	Very High

Based on Table 4, students' understanding of ESD concepts falls within the moderate category, indicating that students have a basic understanding of sustainability concepts but may still require further reinforcement through learning activities. In contrast, the implementation of Green Chemistry principles, relevance to sustainability issues, and improvement in students' understanding are categorized as high. These findings suggest that Green Chemistry-based organic chemistry laboratory practices have contributed positively to connecting laboratory activities with sustainability concepts. Meanwhile, the role of digital innovation and the need for material development are categorized as very high, showing that students perceive digital support and additional ESD-related materials as important components in strengthening sustainable chemistry learning. Overall, the findings indicate that students recognize the importance of integrating ESD and Green Chemistry principles into organic chemistry laboratory practices. The detailed interpretation of each aspect is discussed further in the following sections.

Students' Understanding of ESD Remains Moderate

The findings indicate that students' understanding of Education for Sustainable Development (ESD) concepts remains at a moderate level (60%). This result suggests that although students have participated in Green Chemistry-based organic chemistry laboratory activities, their understanding of sustainability concepts has not yet reached an optimal level. The finding may reflect the fact that students are more familiar with the practical implementation of environmentally friendly laboratory practices than with the broader conceptual framework of ESD itself. The moderate level of understanding observed in this study indicates that students may not yet fully associate laboratory activities with broader sustainability issues. While laboratory experiences can introduce environmentally friendly practices, students may not always connect these experiences to wider sustainability considerations. As a result, sustainability may be perceived primarily as an environmental issue rather than as a concept that involves multiple interconnected dimensions.

Interestingly, this finding contrasts with students' positive perceptions of the implementation of Green Chemistry principles, the relevance of laboratory activities to sustainability issues, and the role of digital innovation in learning. Although students recognized the value of environmentally responsible laboratory practices and considered them relevant to sustainability, their understanding of ESD remained relatively limited. This discrepancy suggests that exposure to Green Chemistry practices alone may not be sufficient to develop a comprehensive understanding of sustainability concepts. The findings also indicate a gap between students' experiences in laboratory activities and their conceptual understanding of ESD. Students appear to appreciate the practical aspects of sustainable laboratory work; however, these experiences may not automatically lead to a deeper understanding of the broader purposes and implications of sustainability-oriented education.

Therefore, laboratory learning should provide more opportunities for students to reflect on the connections between chemical processes, environmental challenges, and sustainability issues. This perspective aligns with Zuin et al. (2021), who emphasized that sustainable chemistry education should extend beyond greener materials and methods by incorporating broader dimensions of sustainability, including contextual, ethical, and systemic perspectives. Sustainability concepts should be explicitly integrated into laboratory activities to help students relate chemical processes to environmental and sustainability issues. Such integration can support students in developing a deeper understanding of chemistry beyond procedural skills and recognizing the role of chemistry in addressing sustainability challenges.

Positive Perceptions of Green Chemistry and Sustainability Relevance

Although students' understanding of ESD remained at a moderate level (60%), they reported positive perceptions of Green Chemistry implementation (66%), the relevance of laboratory activities to sustainability issues (80%), and the contribution of Green Chemistry-based laboratory activities to understanding sustainability principles (74%). These findings indicate that students generally perceive laboratory learning as a meaningful context for sustainability-oriented education. The high perception of sustainability relevance suggests that students recognize the connection between laboratory activities and real-world environmental challenges rather than viewing laboratory work solely as procedural academic tasks.

However, the findings reveal a gap between students' positive perceptions of sustainability-oriented laboratory practices and their conceptual understanding of ESD. Although students recognized the relevance of Green Chemistry and sustainability in laboratory learning, their moderate ESD understanding suggests that engagement with sustainable laboratory practices alone may not be sufficient to develop a deeper understanding of sustainability concepts. Students may benefit from learning experiences that explicitly connect chemical processes, environmental impacts, and sustainable development goals to strengthen their understanding of the broader role of chemistry in sustainability. This finding supports previous perspectives in sustainable chemistry education that emphasize

the need to move beyond the implementation of greener laboratory practices by integrating broader sustainability concepts and helping students understand the role of chemistry in addressing environmental and societal challenges (Zuin et al., 2021).

The Role of Digital Innovation in Laboratory Learning

The role of digital innovation received one of the highest ratings in this study (83%), indicating that students perceive digital technologies as highly valuable in supporting laboratory learning. The findings suggest that digital tools have become an essential component of laboratory education by providing accessible learning resources, supporting the review of laboratory procedures, facilitating access to information, and reinforcing students' understanding of experimental activities. This highlights that technology is no longer viewed merely as a supplementary resource but as an integral part of the learning process. Similar findings have been reported in studies showing that digital technologies can enhance engagement and support chemistry learning through various instructional approaches, including virtual laboratories and interactive learning environments (Ali et al., 2023; Chan et al., 2021). Furthermore, the positive responses suggest that students are receptive to the integration of technology in sustainability-oriented laboratory learning. This finding highlights the potential of digital innovation to support laboratory experiences that are more engaging and relevant to the needs of contemporary education and sustainable development.

Implications for Curriculum and Material Development

The highest score in this study was found in the need for additional ESD-related learning materials (85%). This suggests that students perceive the current learning resources as insufficient to help them understand sustainability concepts in laboratory learning. The strong demand for additional materials shows that students are aware of the importance of sustainability issues and expect these topics to be explained more clearly within chemistry education. This finding aligns with Araripe & Zeidler (2024), who emphasized the importance of integrating Green Chemistry and sustainable chemistry into the curriculum to prepare students to think systematically and act ethically and responsibly. Although students reported positive perceptions of Green Chemistry practices and the relevance of sustainability in laboratory learning, the very high demand for additional materials suggests that awareness of sustainability does not necessarily translate into a comprehensive understanding of ESD concepts. This finding is consistent with previous studies emphasizing that sustainability and green chemistry should be integrated explicitly into chemistry curricula and teaching materials, rather than being addressed solely through laboratory activities (Savec & Mlinarec, 2021).

4. Conclusion

This study found that chemistry education students generally had positive perceptions of Green Chemistry-based laboratory activities and the use of digital

technology in laboratory learning. Students considered laboratory activities relevant to sustainability issues and expressed a strong need for additional learning materials related to Education for Sustainable Development (ESD). However, their understanding of ESD concepts remained at a moderate level. These findings suggest that positive perceptions of sustainability-oriented laboratory learning do not necessarily correspond to a strong conceptual understanding of ESD. While students were aware of the importance of sustainability in laboratory practices, their understanding of the broader principles and objectives of sustainable development was still limited.

This study highlights a gap between students' positive experiences in Green Chemistry-based laboratory learning and their understanding of ESD concepts. The findings indicate that participation in sustainability-oriented laboratory activities does not automatically lead to a comprehensive understanding of ESD. Therefore, chemistry lecturers and curriculum developers need to integrate ESD concepts more explicitly into laboratory learning through appropriate learning objectives, reflective activities, and digital learning resources. Such efforts may help students connect laboratory experiences with broader sustainability issues and strengthen their understanding of sustainable development in chemistry education.

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