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Enhancing 21st Century Skills through Sustainable Inorganic Chemistry Teaching Materials Development from Recycled Materials: Integrating SDGs in Chemistry Learning Media

Siti Marfu'ah[1], Ratna Farwati[2,*], Annisa Meristin[3], Dimi A. Franzizko[4], Pelangi A. E. Putri[5], Farach E. Wardani[6]

[1,2,4,5,6]Chemistry Education, Fakultas Ilmu Tarbiyah dan Keguruan, Universitas Islam Negeri Raden Fatah Palembang, Jl. Pangeran Ratu, 5 Ulu, Seberang Ulu 1, Palembang 30252, Indonesia.

[3]Chemistry Education, Fakultas Keguruan dan Ilmu Pendidikan, Universitas Lampung, Jl. Prof. Dr. Sumantri Brojonegoro No.1 Bandar Lampung, 35145, Indonesia.

Corresponding author*
ratna.farwati@radenfatah.ac.id

Abstract: The development of effective and sustainable teaching materials for inorganic chemistry presents a significant challenge in higher education, especially considering resource limitations and the need to integrate sustainability principles. This study aims to analyze the creativity of students in developing inorganic chemistry learning media based on recycled materials, as well as to explore the integration of Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). A total of 26 students enrolled in the Chemistry Learning Media course over one semester participated in this project. A descriptive qualitative method with a case study approach was employed in this research. The process consisted of four main stages: project orientation, media development, presentation and evaluation, and reflection. Data were collected through observations, documentation, interviews, and product assessments. The findings indicate that students successfully created chemistry learning media with high levels of creativity and complexity using recycled materials such as cardboard, plastic bottle caps, marbles, and used LEDs, representing various inorganic chemistry concepts. This project also contributed positively to students' understanding of chemical concepts, development of 21st-century skills (such as creativity, innovation, collaboration, communication, and problem-solving), and increased awareness of environmental and sustainability issues. These findings highlight the importance of developing innovative and eco-friendly learning media as part of sustainable educational practices in higher education.

Keywords: 21st-century skills, inorganic chemistry, learning media development, recycled materials, SDGs, student creativity, teaching materials.

Introduction

Chemistry education at the higher education level faces challenges in presenting abstract concepts in ways that are more concrete and accessible for students. One solution to address this issue is the use of effective and innovative instructional media. However, the development of learning media is often constrained by limited resources and budget (Eilks & Hofstein, 2013; Gibby et al., 2002; Maleko Munguatosha et al., 2011; Sofi-Karim et al., 2023).

The Chemistry Learning Media course plays a crucial role in preparing future chemistry teachers to develop and utilize effective instructional media. In this context, inorganic chemistry instruction at the higher education level faces significant challenges in presenting abstract and microscopic concepts. Students often struggle to understand various chemical phenomena that cannot be directly observed, such as atomic structure, chemical bonding, and reaction mechanisms (Ali et al., 2022; Cooper & Klymkowsky, 2013; Dood & Watts, 2022; Macrie-Shuck & Talanquer, 2020;

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Marfu'ah et al., 2022, 2023; Marfu'ah & Anwar, 2018; Pölloth et al., 2023; Stroumpouli & Tsaparlis, 2022; Taskin & Bernholt, 2014; Tümay, 2016). The appropriate use of instructional media is essential in helping students visualize and better comprehend these concepts.

On the other hand, the increasingly urgent global environmental issues demand a transformation in higher education practices. The accumulation of waste, particularly on campuses, highlights the need for innovation in resource management and the development of environmental awareness among academic communities. The Chemistry Learning Media course holds strategic potential to integrate these aspects through the development of instructional media based on recycled materials. Previous studies have demonstrated the effectiveness of using recycled materials in science education (Garner et al., 2014; Hole & Hole, 2020; Meristin et al., 2022; Nadi et al., 2016; Ng et al., 2024; Prajoko et al., 2017; Ugulu, 2019; Van De Wetering et al., 2022; Yeboah et al., 2017). However, there is still limited research exploring in depth the creative processes of students in developing inorganic chemistry instructional media based on recycled materials, especially in the context of higher education in Indonesia.

The United Nations' Sustainable Development Goals (SDGs) emphasize the importance of quality education (SDG 4), sustainable consumption (SDG 12), and heightened environmental awareness as vital components of global development. The development of chemistry learning media from recycled materials not only supports the achievement of these goals but also provides meaningful learning experiences for chemistry teacher candidates. Through the process of designing and developing instructional media, students can enhance their creativity while fostering an awareness of responsible waste management.

The use of recycled materials as instructional media for inorganic chemistry opens opportunities to create affordable and eco-friendly educational innovations. This approach enables students to explore the potential of simple materials to explain complex concepts while fostering an understanding of circular economy principles within the context of higher education. Additionally, the development of recycled-material-based instructional media offers a practical solution to the resource and budget constraints often faced by educational institutions.

Based on this urgency, this study aims to develop 21st-century skills among students in creating inorganic chemistry learning media utilizing recycled materials, while also exploring the integration of the Sustainable Development Goals (SDGs), specifically SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Materials and Methods

Study area

This research employs a descriptive qualitative approach with elements of collective case studies (Creswell & Poth, 2016). This approach was chosen to gain an in-depth understanding of the creative processes and outcomes of media development undertaken by students, as well as to explore how the principles of the Sustainable Development Goals (SDGs) are integrated into the project.

The participants in this study consisted of 26 students from the 2023 cohort, divided into two classes, each comprising 13 students, who enrolled in the Chemistry Learning Media course for one semester (16 weeks) at a public university in Indonesia. Participants were selected using purposive sampling techniques based on the following criteria: (1) enrollment in the Chemistry Learning Media course, and (2) willingness to participate in the study.

Procedures

This research was conducted through four main stages over the course of one semester (16 weeks). The first stage, orientation and project introduction, took place during the first two weeks, focusing on the introduction of learning media concepts and the Sustainable Development Goals (SDGs), as well as the assignment of the project to develop inorganic chemistry learning media utilizing recycled materials. In the second stage,

which lasted for 10 weeks (weeks 3-12), students worked in small groups of 2-3 members to design and develop the learning media. During this period, each group held regular consultations with the supervising lecturer to receive guidance and feedback on their progress in developing the learning media. The third stage lasted for three weeks (weeks 13-15) and focused on the presentation and evaluation of project outcomes. Each group presented the learning media they had developed, followed by peer evaluation and constructive feedback from the supervising lecturer. The final stage took place in week 16, where students reflected on the process and results of the project, as well as refined the learning media based on the input received during the presentation and evaluation sessions

Data analysis

Data collection was conducted using four main methods to ensure data triangulation. First, participant observation was carried out during the project development process to observe group dynamics and the progress of the learning media. Second, documentation of the process was done through the collection of project logbooks and photographic and video documentation of the developed learning media. Third, semi-structured interviews were conducted with 10 representative students from each group to gain in-depth insights into their experiences and perspectives. Fourth, the final product was assessed using a rubric that included aspects of creativity, relevance of inorganic chemistry content, and integration of the SDGs.

Data analysis utilized a thematic analysis approach (Braun & Clarke, 2006) with the assistance of NVivo 12 software, following five systematic stages: familiarization with the data through transcription and repeated reading, inductive initial coding, searching for and reviewing themes, defining and naming themes, and producing the final report. To ensure the validity of the data, the researcher implemented member checking by verifying data interpretations with participants, as well as peer debriefing through discussions of findings with colleagues not directly involved in the research.

Results and Discussion

Result-1 Innovation in the Utilization of Materials and Relevance to Inorganic Chemistry Content

The analysis results indicate that students demonstrated a significant level of creativity in utilizing various types of recycled materials to develop inorganic chemistry learning media. This creativity is reflected not only in the selection of materials but also in the transformation process of these materials into effective and functional learning media (Bereczki & Kárpáti, 2021; Carvalho & Yeoman, 2021; Kwangmuang et al., 2021; Marfu'ah et al., 2022; Marfu'ah & Anwar, 2018). An analysis of the produced products revealed several aspects of innovation that can be categorized into three main dimensions: design complexity, utility of materials, and the level of interactivity of the media, along with the relevance of the inorganic chemistry content presented in Table 1.

Table 1. Analysis of Learning Media Products Based on Recycled Materials.

Group	Product	Main materials	Design Complexity	Level of Interactivity	Represented Chemistry Concepts
1	Atomic Model	Cardboard, bottle caps, used balls, styrofoam, wire	High	Medium	Development of atomic models from Dalton to Bohr
2	Periodic Table	Styrofoam, used cardboard, used LEDs	Medium	High	Periodic trends
3	Molymod	Used marbles, plastic straws	Medium	High	Molecular structure, chemical bonds
4	Electron Configuration	Bottle caps, cardboard,	High	High	Aufbau principle, electron

Group	Product	Main materials	Design Complexity	Level of Interactivity	Represented Chemistry Concepts
	Simulator	used cables			configuration
5	Miniature Acid Rain Simulation	Cardboard, plastic bottles, used hoses	High	Medium	Acid-base reactions, environmental impact
6	Atomic Structure Model	Bottle caps, cardboard, used LEDs	Medium	High	Atomic structure, electron orbitals

Result-2 Integration of Sustainability Principles

Data analysis indicates that the project for developing learning media based on recycled materials successfully integrated several principles of the Sustainable Development Goals (SDGs) set by the United Nations. The research findings suggest that this project contributes to achieving at least three SDGs: SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Table 2 presents the integration of the SDGs within the learning media project, while Table 3 displays students' perceptions of the integration of the SDGs.

Table 2. Integration of SDGs in the Learning Media Project.

SDG	Aspect	Findings
SDG 4	Improvement in Concept Understanding	85% of students reported better understanding and 78% felt more confident.
	Development of 21st-Century Skills	Encourages skills such as creativity, collaboration, and problem-solving.
	Contribution to Innovative Learning	Enriches chemistry learning practices with creative approaches.
SDG 12	Utilization of Recycled Materials	100% of media utilized used materials.
	Waste Reduction	Encourages reduction of waste production on campus.
	Promotion of Circular Economy	Using recycled materials demonstrates the potential for a circular economy.
SDG 13	Increased Environmental Awareness	92% of students enhanced their understanding of the environmental impact of waste.
	Promotion of Sustainable Practices	Encourages the application of sustainability principles in learning.
	Contribution to Green Campus Transformation	This project has the potential to serve as a model for green campus initiatives.

Table 3. Students' Perceptions of the Integration of SDGs.

Respondent	Statement
Student A	"This project opened our eyes to how we can contribute to the SDGs through simple actions in learning."
Student B	"Transforming waste into effective learning media made us aware of the potential of recycled materials."

Result-2 Development of 21st-Century Skills

In addition to understanding inorganic chemistry content and integrating sustainability principles, this research also identifies the positive impact of the project on the development of 21st-century skills among students. Data analysis indicates that the design and creation process of learning media based on recycled materials contributes to the enhancement of various essential 21st-century skills, such as creativity, innovation, collaboration, communication, problem-solving, and digital literacy. Table 4 summarizes the information regarding the development of 21st-century skills within this media project.

Table 4. Development of 21st-Century Skills Through the Learning Media Project.

Skill Aspect	Findings
Creativity and Innovation	• 92% of products demonstrated a high level of creativity. • Students created varied media designs. • Ability to combine materials for unique representations.
Collaboration and Communication	• Improvement in teamwork abilities. • 85% of students reported positive experiences in discussions. • Presentations encouraged clear communication of ideas.
Problem-Solving	• 78% of students identified and addressed technical challenges. • Ability to develop adaptive strategies. • Iterative processes fostered critical thinking.
Digital Literacy	• 73% of students engaged in process documentation using digital technology. • Utilization of simple electronic components. • Digital presentations enhanced presentation skills.

Discussion-1 Innovation in the Utilization of Materials and Relevance to Inorganic Chemistry Content

Based on Table 1, observations of the media development process indicate that students were able to produce designs with varying levels of complexity, ranging from simple to complex. In the realm of design, the complexity of a project can be measured by the number of components involved and the difficulty level of the creation process. Designs can be categorized into three levels: low, medium, and high. Meanwhile, the level of interactivity also plays a crucial role, referring to the extent to which users can interact with the presented media. This level of interactivity is further divided into three categories: low, medium, and high. By considering these two aspects, designers can create works that are not only aesthetically pleasing but also engaging and functional for users.

In-depth interviews with students revealed a systematic creative process in the development of learning media. Several representative quotes illustrate this:

> *"At first, we were confused about how to transform waste into tools for learning inorganic chemistry. But after discussing and exploring various concepts, we began to see the potential in each recycled material to explain topics like atomic structure or chemical reactions." (Student A, Interview)*

> *"The biggest challenge was ensuring that the media we created was not only visually appealing but also accurate in representing chemical concepts. We went through many revisions to achieve this." (Student B, Interview)*

The process of developing learning media consists of four main stages outlined by Wilson et al. (2021). The first stage is exploration and material collection, which typically takes one to two weeks. Next, during the design and prototyping stage, designers spend about two to three weeks creating sketches and initial models. Following this, the development and testing stage lasts for three to four weeks, during which the designed media is tested to ensure its functionality. Finally, evaluation and refinement are conducted over two weeks to ensure that the produced learning media meets the expected quality and effectiveness standards.

Students' reflective analysis indicates that the process of developing learning media based on recycled materials significantly contributed to their understanding of inorganic chemistry concepts. This finding aligns with Hernández-Leo et al., (2019), which shows a positive correlation between engagement in the creation of learning media and mastery of science concepts.

> *"Creating an atomic model from recycled materials forced us to truly understand the structure and characteristics of each atomic model. We couldn't create an accurate representation without a deep understanding." (Student C, Interview)*

The creativity in utilizing recycled materials confirms and expands upon the findings of Rodriguez-Losada et al. (2017) regarding the potential of everyday materials in science education, particularly in the context of inorganic chemistry. Furthermore, these results support the research of Barak & Dori (2005), Domenici (2022), Erdem (2012), Li et al. (2022), Schneider et al. (2022), Tian et al. (2023), and Zhao & Wang (2022), which demonstrates the effectiveness of project-based learning approaches in enhancing conceptual understanding in chemistry.

Although the results obtained indicate positive outcomes, students faced several challenges during the development process of the learning media. A total of 73% of respondents reported limitations in the physical characteristics of the recycled materials they used. Additionally, 65% of respondents encountered difficulties in ensuring the accuracy of conceptual representations, while 58% faced challenges in integrating multiple representations.

To address these challenges, students formulated various adaptive strategies. They combined different types of materials to achieve the desired representation, held regular consultations with their supervising lecturers to ensure conceptual accuracy, and utilized simple technologies, such as recycled LEDs, to enhance the interactivity of the developed media. These findings not only enrich the literature on project-based learning in chemistry education (Johnson, 2023) but also provide new insights into how resource limitations can act as a catalyst for creativity in the development of learning media.

Discussion-2 Integration of Sustainability Principles

Data analysis indicates that the project for developing learning media based on recycled materials successfully integrated several principles of the Sustainable Development Goals (SDGs) established by the United Nations. The research findings suggest that this project contributes to the achievement of at least three SDGs: SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

The development of innovative and effective learning media is an integral part of efforts to improve educational quality, in line with the goals of SDG 4. The research results demonstrate that this project has successfully supported the realization of SDG 4 through several important aspects. First, regarding the enhancement of conceptual understanding, 85% of students reported having a better understanding of inorganic chemistry concepts after engaging in the development of the learning media. Additionally, 78% of students felt more confident in explaining these concepts.

Furthermore, this project also promotes the development of 21st-century skills, including creativity, collaboration, communication, and problem-solving. Observations conducted indicate an improvement in students' abilities to work together and communicate ideas effectively.

Lastly, the development of learning media based on recycled materials enriches chemistry education practices at the higher education level, allowing students to explore creative approaches to enhance the quality of science learning. These findings align with (UNESCO's (2017) recommendations regarding the importance of integrating Education for Sustainable Development (ESD) into higher education curricula.

This project also contributes to the realization of SDG 12, which emphasizes sustainable consumption and production. This contribution is evident through several aspects. First, in the utilization of recycled materials, all learning media were developed using waste materials such as cardboard, plastic bottles, and styrofoam. Students successfully transformed this waste into valuable resources for learning.

Furthermore, this project encourages the reduction of waste production on campus, where students demonstrate an awareness of the importance of responsible waste management. Additionally, the use of recycled materials in the development of learning media showcases the potential for a circular economy in the academic environment, with students exploring more sustainable consumption and production models. These results further reinforce the argument put forth by Garner et al. (2015), Hodson (2003) and

Liarakou (2019) stating that science education based on recycled materials can support responsible consumption and production.

This project also makes a significant contribution to achieving SDG 13, which focuses on addressing climate change. Several aspects integrated into this project include enhancing environmental awareness. A total of 92% of students reported that the project has increased their understanding of the environmental impact of waste and trash, as well as demonstrating a commitment to reducing their carbon footprint in daily life.

Furthermore, this project promotes sustainable practices by encouraging students to apply sustainability principles in their learning and campus activities. Students also explored the potential of recycled materials as resources that can be utilized responsibly.

Additionally, this project has the potential to serve as a model for green campus initiatives at other institutions. The development of learning media based on recycled materials can be adopted as a sustainable practice within the campus environment. These findings align with previous research indicating that project-based science education can support education for sustainable development, as highlighted by Garner et al. (2015) and Rodriguez-Losada et al. (2017).

Table 3 shows the results of interviews with students, revealing their understanding and appreciation of the integration of SDG principles in this project. These findings enrich the literature on the integration of SDGs in higher education practices, particularly in the context of developing innovative learning media (Leal Filho et al., 2022).

Discussion-3 Development of 21st-Century Skills

In addition to understanding inorganic chemistry content and integrating sustainability principles, this study also identifies the positive impact of this project on the development of 21st-century skills among students. Data analysis shows that the process of designing and creating learning media based on recycled materials contributes to enhancing various essential 21st-century skills, such as creativity, innovation, collaboration, communication, problem-solving, and digital literacy. This study also identifies the positive impact of this project on the development of 21st-century skills among students.

Research findings indicate that this project successfully fosters creativity and innovation among students. Approximately 92% of the educational media products produced demonstrated a high level of creativity in utilizing recycled materials. Students not only managed to produce a variety of media designs, ranging from simple to complex, but also showed the ability to combine different types of materials to create unique conceptual representations. These findings are in line with previous research emphasizing the importance of project-based learning in developing creativity and innovation skills, as noted by Asbjornsen (2015), Barak & Dori (2005), Barak & Yuan (2021), Chen et al. (2022), de Oliveira Biazus & Mahtari (2022), Hwang et al. (2017) and Isabekov & Sadyrova (2018).

Data analysis reveals that this project significantly contributes to enhancing collaboration and communication skills among students. Observations noted an improvement in students' ability to work effectively in small groups. A total of 85% of students reported positive experiences when discussing, exchanging ideas, and integrating diverse perspectives. Additionally, project presentations and evaluation sessions encouraged students to communicate their ideas and findings clearly and persuasively. These results support the arguments made by Chua and Chai (2016) regarding the importance of project-based learning in developing essential collaboration and communication skills in the 21st century.

The process of developing learning media based on recycled materials has proven effective in enhancing problem-solving skills among students. About 78% of students reported experiences in identifying and overcoming various technical challenges that arose during media production. Observations indicated that students were able to develop adaptive strategies to address material limitations and ensure conceptual representation accuracy. Furthermore, interviews revealed that the iterative process of refining products encouraged students to think critically and solve

problems creatively. These findings reinforce previous research indicating a positive correlation between project-based learning and the development of problem-solving skills, as shown by Johnson et al. (2023) and Zhang et al. (2022).

Although not the main focus, this project also contributes to enhancing digital literacy among students. A total of 73% of students participated in documenting the media development process using digital technologies, such as photos, videos, and presentations. Additionally, the use of simple electronic components, such as LEDs, in some learning media encouraged students to explore technology. Project presentations conducted in digital formats also helped students develop effective presentation skills. These findings expand the understanding of the potential of project-based learning to integrate aspects of digital literacy, as articulated by Almazroui (2023) Artama et al. (2023), Martinez (2022) and Pawar et al. (2020).

These findings enrich the literature on the effectiveness of project-based learning in science education (Andriyani et al., 2019; Balemen & Keskin, 2018; Bilgin et al., 2015; Chistyakov et al., 2023; Ergül & Kargın, 2014; Gangwar, 2017; Khaliq et al., 2015) and provide new insights into the potential of using recycled materials as a catalyst for developing 21st-century skills.

Conclusions

This study concludes that the development of inorganic chemistry learning media based on recycled materials can be an effective strategy for enhancing students' understanding of complex inorganic chemistry concepts. Furthermore, this project successfully integrates the principles of the Sustainable Development Goals (SDGs) established by the United Nations, particularly regarding quality education (SDG 4), responsible consumption and production (SDG 12), and climate action (SDG 13). Through the design and creation process of learning media, students not only demonstrated significant creativity and innovation but also developed essential 21st-century skills, such as creativity, innovation, collaboration, communication, problem-solving, and digital literacy. The findings of this research enrich the literature on the potential of project-based learning in science education, while also providing new insights into the integration of sustainability principles in higher education teaching practices.

Conflict of Interest: The authors declare that there are no conflicts of interest concerning the publication of this article.

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