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A Vitual Reality Digital Comic: Fostering Environmental Literacy through Baduy Local Wisdom

Khoirunnisa Khoirunnisa[1]✉, Sudarmin Sudarmin[1], Sigit Priatmoko[1], Nunung Nurhayati[2]

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[1]Universitas Negeri Semarang, Indonesia
[2]Universitas Setia Budhi Rangkasbitung, Indonesia

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Abstract

The objectives of this study are developing and evaluating the effectiveness of a digital comic based green chemistry instructional materials integrated with Virtual Reality (VR) and Baduy local wisdom to improve students' sustainable environmental literacy. Utilizing Research and Development (R&D) method using 4D model, all instructional components (VR digital comic, teaching module, test instruments, and questionnaires) were validated by experts and deemed highly valid (Aiken's V > 0.80). A try out of the VR digital comic media with small scale revealed enggaging category with an average percentage exceeding 90%. The Independent Sample t-Test in the experimental and control classes showed a statistically significant difference in posttest scores (Sig. <.001), proving a substantial increase in learning outcomes in the experimental class. Environmental literacy analysis based on the National Environmental Literacy Assessment (NELA) indicators supports these findings: the experimental group achieved a high-level criterion (score: 190) compared to the control group (score: 169). The most prominent improvement in the experimental class was observed in the knowledge and cognitive skills dimensions. The implementation of this learning innovation effectively improves students' environmental literacy, particularly in knowledge and cognitive skills. Nevertheless, the development of deeply internalized environmental attitudes and behaviors may require more time and a more in-depth approach. However, but this innovation shows significant potential in shaping a generation responsible for environmental issues.

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✉ Correspondence Author:
E-mail: nisakhoirunnisa1213@students.unnes.ac.id

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INTRODUCTION

Literacy is basicaly defined as reading and writing ability (Liu et al., 2024). The concept of literacy has expanded over time in response to technological advancements (Ika et al., 2024). Today, literacy encompasses not only reading, writing, and numeracy, but also includes digital literacy, media literacy, and education for sustainable development (UNESCO, 2025). This expansion reflects that students should be equipped with wider range of skills to deal with ever-more complex environmental, technical, and social concerns (Wang & Zhang, 2021). A key aspect of this is environmental literacy (Xiong et al., 2025). It is considered a primory solution to addressing various environmental problems caused by human activities (Harris et al., 2025). Environmental literacy is the ability to understand and apply sustainability princi-ples in everyday life (Henukh et al., 2025). Nowadays, it is regarded as the main strategy for dealing with ecological problems (Pouresmaieli et al., 2024).

The integration of green chemistry into education plays a significant role to train students' awareness and sensitivity toward environmental problems encountered in daily life (L´opez-Fern´andez et al., 2025). Green chemistry refers to a more environmentally friendly production method that minimizes the use of hazardous chemicals and produces more efficient process (Amoneit et al., 2024). Green and sustainable chemistry principles are not only applied in research and industry but can also be integrated into chemistry education, from secondary to tertiary levels (Araripe & Zeidler, 2024). These principles are particularly important in laboratory experiments, as experiments using chemicals have the potential to produce waste that can pollute the environment (Zidny & Eilks, 2022).

Schools serve as the foundation of early education for students; therefore, the integration of green chemistry is expected to cultivate a generation that is responsible for the environment in the future (Zidny & Eilks, 2022). Indonesia is rich in ethnic and cultural diversity, one of which is the Baduy tribe in Kenakes Village, Leuwi Damar District, Lebak Regency, Banten Province (Wicaksono et al., 2022). The Baduy community is an indigenous group that upholds strong cultural values and local wisdom in maintaining the balance of nature (Kenedy & Deffinika, 2022). They possess traditional knowledge about sustainability and ecosystem preservation (Zidny et al., 2021). Integrating such indigenous ecological knowledge into educational material can improve students' environmental literacy (Silva et al., 2024). However, there is still little integration of this kind in the educational media used today. The learning media commonly used in schools are still rely on printed textbooks, which are less engaging and and lack integration with modern technologies and local contexts relevant to students' lives (Mhlongo et al., 2023).

One increasingly popular innovation in learning is the use of digital comics (Nabila, 2025). Digital comics offer an engaging and interactive visual approach, which can increase students' interest and understanding of the subject being taught (Cook & Hest, 2025). Furthermore, technology integration into learning media has been shown to improve creativity, learning motivation, and conceptual understanding more effectively than traditional methods (Haleem et al., 2022). In addition, technological developments such as artificial intelligence (AI) and the Internet of Things (IoT) have introduced the concept of the metaverse (Roy et al., 2025), creating new opportunities for innovation in education. For instance, the integration of digital technology into instructional media is the use of virtual reality (VR) (Almeman et al., 2025).

The use of VR in cemistry learning has been shown to improve student motivation, critical thinking skills, and interest in the subject matter (Viitaharju et al., 2023). Previous research has demonstrated that virtual reality-based learning media not only clarify abstract concepts but are also more easily accepted by students compared to conventional teaching methods (Portuguez-castro & Garduño, 2024). Therefore, the development of innovative VR-based learning media can be an effective solution for improving students' understanding (Rizvan et al., 2023) of green chemistry concepts in schools.

Despite growing evidence of the usefulness of VR and the significance of green chemistry, there are still few educational materials that combine VR technology (Muslich, 2025), green chemistry principles, and local knowledge especially indigenous environmental knowledge from groups like the Baduy. Current virtual reality resources mostly concentrate on general chemistry topics, paying little regard to cultural contextualization or sustainability considerations. In the meanwhile, research that integrate local knowledge into educational materials using VR is infrequently used (Samala et al., 2025). Thus, the development of VR-based learning media integrating green chemistry principles and Baduy local wisdom offers a novel contribution to the field.

METHOD

This research employed a Research and Development (R&D) approach, adopting the 4D development model developed by Thiagarajan, Semmel, and Semmel. The model consists of four main stages, Define, Design, Develop, dan Disseminate. This model is selected duet to its goal to produce learning media that are valid effective, and aligned with students' learning needs.

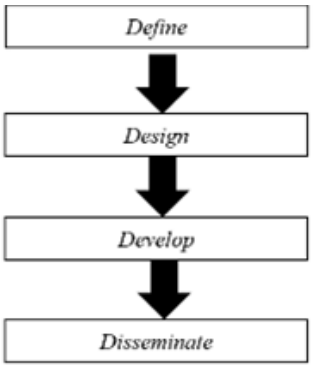

Figure 1. Steps in 4D Development

The first stage, Define, was carried out to identify learning needs and problems en-countered in teaching green chemistry con-cepts. Activities at this stage are searching for and analyzing information sources relat-ed to the research conducted by literature studies, analyzing the curriculum, identify-ing learning media needs, selecting software to develop learning media, and analyzing green chemistry material that align with the local wisdom of the Baduy indigenous community.

The second stage, Design, involved designing digital comic learning media integrated with Virtual Reality. This stage involved developing a storyline, creating comic visual, uploading the comic to the Virtual Reality platform, providing user instructions, and selecting background music. In addition, this stage included creating a storyboard. The product was then created and validated by a chemistry lecturer and a media expert. The learning media design is also developed. Furthermore, this stage included developing supporting instruments to be used, such as validation sheets.

The third stage, Develop, focused on revising product based on chemistry and media expert. Afterward, the learning media was piloted on students. Feedback was collected through questionnaires completed by both teachers and students to assess the practicality and appeal of the media. Data collection was conducted using expert validation sheets, student questionnaires, and teacher questionnaires focusing on practicality, usability, and attractiveness. The obtained data were analyzed using descriptive statistics. Whereas, qualitative feedback from experts and users was analyzed through thematic categorization to identify improvement areas. For interpretation, it was conducted out by comparing the results with predetermined validity and practicality criteria to conclude whether the media met acceptable standards and required further refinement.

The fourth stage, Disseminate, this stage is carried out by registering the developed learning media as Intellectual Property Rights (IPR), and writing research a research aticle for publication, so that everyone can access them. Through these stages, it is expected that the developed learning media will become an innovative solution in chemistry learning, especially in the teaching green chemistry, while at the same time instilling environmental conservation values based on the local wisdom of the Baduy people to the younger generation.

Prior to their implementation in the research, all instructional components were validated by experts and assessed using Aiken's V formula. The validation process of Virtual Reality integrated digital comics was assessed by 5 validators with a 5-point Likert scale. After obtaining the calculated V value, the value was then compared with the V value of the Aikens index table by setting an error rate of 5% (0.05). A component was considered valid if the calculated V value was ≥ 0.80. For the teaching modules, test instruments and questionnaires, they were assessed by 3 validators using a validation instrument with a 5-point Likert scale.

A small-scale trial was conducted to evaluate the developed Virtual Reality–integrated digital comic. This trial involved a group of 11th-grade students as respondents. Evaluation was carried out using a questionnaire. An Independent Sample t-Test was utilized as a statistical method to determine whether there was a significant difference in the mean scores between two independent groupscommonly used to compare the outcomes of an experimental group and a control group. The Independent Sample t-test is used to compare the means of two unrelated groups, whose data are normally distributed and homogeneous. A normality test was conducted using the Kolmogorov-Smirnov test, which was used to determine whether data in a population has a random and specific distribution. In the Kolmogorov-Smirnov test, if the Sig value is > 0.05, then the data from the pretest and posttest

results of students are normally distributed. The homogeneity test at this stage was conducted to determine whether the pretest and posttest data had the same variance or not. The homogeneity test used was Levene's test. This test is required as one of the requirements before conducting a difference test (Independent t-Test). In the homogeneity test, if the Sig. value is > 0.05, the pretest and posttest data are homogeneous. In analyzing students' environmental literacy improvements, a questionnaire that compiled based on the National Environmental Literacy Assessment (NELA) indicators was employed. Students' environmental literacy scores were categorized into three classifications: low (27-98), moderate (99-169), and high (170-240).

RESULT AND DISCUSSION

The main components used in this study are teaching devices and instruments that served as learning support and experimental data collection tools. These components included Virtual Reality integrated digital comic learning media, teaching modules, test instruments, and questionnaire instruments that aim to improve sustainable environmental literacy. Prior to their implementation in the research, all instructional components were validated by experts and assessed using Aiken's V formula. The validation process of Virtual Reality integrated digital comics was assessed by 5 validators with a 5-point Likert scale. After obtaining the calculated V value, the value was then compared with the V value of the Aikens index table by setting an error rate of 5% (0.05). A component was considered valid if the calculated V value was ≥ 0.80. For the teaching modules, test instruments and questionnaires, they were assessed by 3 validators using a validation instrument with a 5-point Likert scale. A calculated Aiken's V score ≥ 0.92 was categorized as valid, in accordance with Aiken (1985). The results of the validation test on the teaching tools used can be seen in Table 1.

Table 1. Validation Results

Instructional Components	Aiken's V Score	Category
Virtual Reality–Integrated Digital Comic	0.87	Valid
Teaching module	0.93	Valid
Test Instrument and Questionnaire	0.93	Valid

The validation results showed that all components of the teaching materials, including the teaching modules, test instruments, and questionnaires, received an average score of highly valid. These findings showcased that the developed teaching materials are suitable for use in green chemistry-based chemistry learning, integrated with digital comics and virtual reality based on the local wisdom of the Baduy community.

A small-scale trial was conducted to evaluate the developed Virtual Reality–integrated digital comic. This trial involved a group of 11th-grade students as respondents. Evaluation was carried out using a questionnaire with a rating scale covering four main aspects: instructional quality (91%), content relevance (91%), visual presentation (90%), and readability (90%). The trial results revealed that all aspects received ratings in the "very interesting" category, indicating that the learning media is suitable to be used in the next stage.

An Independent Sample t-Test was utilized as a statistical method to determine whether there was a significant difference in the mean scores between two independent groupscommonly used to compare the outcomes of an experimental group and a control group. The Independent Sample t-test is used to compare the means of two unrelated groups, whose data are normally distributed and homogeneous. A normality test was conducted using the Kolmogorov-Smirnov test, which was used to determine whether data in a population has a random and specific distribution. In the Kolmogorov-Smirnov test, if the Sig value is > 0.05, then the data from the pretest and posttest results of students are normally distributed. The results of the normality test are shown in Table 2.

Table 2. Normality Test

Class	Sig.	Description
Pretest Control Class	0.39	Normally distributed
Pretest Experimental Class	0.37	Normally distributed
Posttest Control Class	0.11	Normally distributed
Posttest Experimental Class	0.21	Normally distributed

The homogeneity test at this stage was conducted to determine whether the pretest and posttest data had the same variance or not. The homogeneity test used was Levene's test. This test is required as one of the requirements before conducting a difference test (Independent t-Test). In the homogeneity test, if the Sig. value is > 0.05,

the pretest and posttest data are homogeneous. The results of the homogeneity test in Table 3.

Table 3. Homogeneity Test

Results	Sig.	Description
Pretest Based on Mean	0.728	Homogeneous
Posttest Based on Mean	0.758	Homogeneous

The results of the homogeneity test for pretest and posttest scores in both the control and experimental classes indicated that the data were homogeneous. After conducting normality and homogeneity tests, an independent sample t-test compared the mean learning outcomes between the experimental group receiving the special treatment and the control group receiving no treatment. If the sig. (2-tailed) value is <0.05, it can be concluded that there is a significant difference in the results of the control and experimental classes. The results of the independent sample t-test for the posttest scores for the control and experimental classes are presented in Table 4.

Table 4. Independent Sample t-Test Result

Posttest Score	Sig.		Description
	One-sided p	Two-sided p	
Equal variances assumed	<.001	<.001	A significant difference exists between control and experimental groups
Equal variances assumed	<.001	<.001	A significant difference exists between control and experimental groups

Based on the information in the Table 4, it can be concluded that there was a significant difference in the learning outcome of control and experimental class. In analyzing students' environmental literacy improvements, a questionnaire that compiled based on the National Environmental Literacy Assessment (NELA) indicators was employed.

Table 5. Environmental Literacy Score Result

Class	Environmental Literacy Score	Category
Control	169	Moderate
Experimental	190	High

The Table 5 shows that the control group achieved an average score of 169, categorized as moderate, while the experimental group scored 190, which falls under the high category. Environmental literacy was assessed across four key aspects: Knowledge, Cognitive Skills, Attitude, and Behavior. The average scores for each aspect in both groups are presented in Table 6.

Table 6. Average Scores by Environmental Literacy Aspect

Aspect	Class	Environmental Literacy Score	Category
Knowlegde	Control	39	Moderate
Kognitive Skill		40	Moderate
Attitude		47	High
Behavior		46	High
Knowlegde	Experiment	45	High
Kognitive Skill		49	High
Atttude		49	High
Behavior		47	High

The results revealed that the average environmental literacy scores in the control group was moderate results in the aspects of Knowledge and Cognitive Skills, and high results in Attitude and Behavior. However, the experimental group achieved high scores for all four aspects. The high score that achieved by the experimental class indicated that the use of the learning media had potential effectiveness to improve environmental literacy (Rahman et al., 2024). The most noticeable score gaps between the experimental and control groups were found in the aspects of Knowledge and Cognitive Skills, while the differences in Attitude and Behavior were relatively smaller (Lestari et al., 2024). Innovative and interactive learning, as applied in the experimental class, effectively improved students' knowledge and critical thinking skills since the material was presented in an engaging, and contextual way that encouraged concept exploratory and problem-solving (Tadena & Salic-Hairulla, 2021). It is occured since the focus of the use of the learning media in the experimental class on conceptual understanding and cognitive development, thus having a significant impact on knowledge and cognitive aspects (Kuhlmann et al., 2024).

Additionally, the use of VR allowed students to experience realistic simulations of the environment and learning concepts (Crogman et al., 2025), thereby boosting their motivation and critical thinking skills in understanding the material (Amirbekova et al., 2024). It demonstra-

ted analytical skills and fostered attitudes toward environmental issues (Fauville et al., 2020). Learning experiences that make students feel connected to nature can foster a sense of care, responsibility, and a willingness to contribute to the environment (Madera et al., 2025).

Environmental issues are inherently complex because they involve many factors, including social, economic, socio-cultural, policy factors, and behavioral dimensions (Kumar et al., 2024). Environmentally responsible behavior can vary across situations (Wu & Tham, 2023). While environmental education provides important foundational knowledge, converting this knowledge into concrete behavior in various situations requires more than just understanding (Husin et al., 2025). It required to translate this knowledge into real-life environmentally responsible behavior (Portus et al., 2024; Begum et al., 2025). Although changes in knowledge and cognitive skills can be relatively easily measured through tests or questionnaires Ardoin et al., (2020), assessing long-term changes in attitudes and especially actual behaviors remains a significant challenge in environmental education research.

CONCLUSION

This study demonstrates that the green chemistry learning tools in the form of a VR-integrated digital comic, which incorporates Baduy local wisdom, are highly valid and engaging. The implementation of this instructional tool significantly improved students' environmental literacy, particularly in cognitive knowledge and skill domains, compared to the control group. However, changes in attitudes and environmental behavior require more time and deeper pedagogical approaches to be fully internalized.

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