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Development of a Virtual Laboratory Media Based on Green Chemistry for High School Students

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ABSTRACT

This study aimed to develop and evaluate a green chemistry–based virtual laboratory for chemical equilibrium topics to enhance senior high school students' analytical thinking skills and environmental awareness. The research employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate). The development stages included expert validation, usability testing by teachers, readability testing by students, and an effectiveness test using a one-group pretest–posttest design. The participants consisted of 67 eleventh-grade students. Data on analytical thinking skills and environmental awareness were analyzed using paired sample t-tests, complemented by effect size (Cohen's d) and normalized gain (N-gain) analyses to determine the magnitude of the learning effect. The results indicated that the green chemistry–based virtual laboratory achieved a very good level of feasibility based on evaluations by experts, teachers, and students. The effectiveness test showed a significant improvement in students' analytical thinking skills, with the mean score increasing from 49.93 to 85.03 ($p < 0.001$), accompanied by a large effect size and a high N-gain category. In contrast, environmental awareness showed a slight increase in mean scores but did not reach statistical significance ($p = 0.494$). These findings suggest that the green chemistry–based virtual laboratory is effective in enhancing students' analytical thinking skills. However, additional and more sustainable instructional strategies are required to achieve a significant improvement in students' environmental awareness.

Keywords: Chemical equilibrium, green chemistry, virtual laboratory.

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INTRODUCTION

Chemistry education is a field within science education that studies the structure, properties, and changes of matter, as well as the energy that accompanies these processes, ranging from the atomic to the macroscopic level. Chemistry education plays a crucial role in shaping students' scientific understanding and honing their critical, logical, and analytical thinking skills. In chemistry learning, these abilities are essential so that students do not merely memorize concepts, but are also able to apply them in real life (Redhana, 2019). However, despite its strategic role, chemistry is known as a subject perceived as difficult by the majority of students.

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Edomwonyi-Otu & Avaa (2011) state that chemistry is generally difficult for students to comprehend. Topics considered difficult include the naming of compounds and their chemical formulas, the concepts of covalent and ionic compounds, polar and nonpolar properties, ionic and molecular reactions, as well as oxidation numbers (Tsaparlis, 2016). Difficulties also arise in topics involving calculations, such as stoichiometry (Yakina & Fadhilah, 2017; Demirdogen & Cakmakci, 2014), and abstract concepts such as chemical equilibrium (Stieff & Wilensky, 2003).

One of the essential strategies to overcome these difficulties is through laboratory activities (practicum). Practicum can help students connect the theories learned in class with real-world phenomena, making abstract concepts more concrete and easier to understand. However, the implementation of practicum in many schools still faces obstacles. One of the main constraints is limited time. Experiment-based learning requires more time compared to learning without laboratory activities (Elisa & Nugraha, 2023; Nais et al., 2019). An ideal practicum process should encompass the stages of exploration, reflection, argumentation, and interaction among students (Tan, 2008); however, this condition is difficult to meet given that school lesson hours are relatively limited. Furthermore, several types of chemistry practicums involve the use of materials or procedures that pose risks to student safety. In certain topics, such as petroleum and hydrocarbons, laboratory activities can present potential hazards, thereby requiring strict safety procedures (Evans et al., 2008).

One of the solutions that can address the constraints of implementing chemistry practicums is the utilization of virtual laboratories. This medium is designed to simulate experimental activities interactively, allowing students to understand scientific concepts that are otherwise difficult to comprehend through conventional learning (Chiu et al., 2015). Virtual laboratories enable the exploration of chemical concepts at various levels of representation, ranging from the microscopic level (Evans et al., 2008; Tatli, 2013), the particulate level (Hawkins & Phelps, 2013), to the abstract sub-microscopic level (Muchson, 2019). This visualization capability helps students build a more holistic understanding, making the acquired chemistry knowledge deeper and more meaningful.

On the other hand, science education also plays a vital role in fostering environmental awareness. According to Amran et al. (2019), environmental awareness is significantly correlated with eco-friendly behaviors, such as energy conservation, waste management, and the safe use of chemical substances. Unfortunately, this aspect still receives insufficient attention in chemistry learning, even though concepts such as laboratory waste, reaction efficiency, and the use of toxic materials are closely linked to environmental issues. According to Tilbury (1995), environmental awareness involves changes in attitude and behavior formed through contextual experiences and reflection on the impact of human activities on nature. On the other hand, the concept of green chemistry formulated by Anastas and Warner (1998) emphasizes the principle of sustainability in chemical sciences through waste prevention, the use of safer chemicals, and energy efficiency. These principles are highly relevant to be integrated into science education in schools.

One of the approaches capable of integrating these cognitive and affective aspects is green chemistry. Green chemistry is a concept in chemical science aimed at designing chemical processes and products that reduce or eliminate the use and generation of hazardous substances (Ravichandran, 2011). The application of green chemistry principles in schools can foster students' awareness of the

environmental impact of chemistry and encourage more responsible behavior. Karpudewan et al. (2012) found that green chemistry-based learning significantly increases students' understanding of environmental sustainability and builds positive attitudes toward science.

Unfortunately, the utilization of green chemistry in education still faces various obstacles. A study by Auliah et al. (2018) states that the majority of teachers do not yet fully understand the concept of green chemistry, and therefore have not been able to integrate it into their teaching. In addition, many schools suffer from a lack of safe, comprehensive, and eco-friendly laboratory facilities. Furthermore, some of the available practicums still use hazardous chemicals or generate toxic waste that is not optimally managed. This situation makes teachers reluctant to conduct laboratory activities, thereby causing students to lose the opportunity to gain meaningful learning experiences.

The solution to these problems can be found through the utilization of technology in learning, particularly through the development of virtual laboratory media. A virtual laboratory is a digital-based medium that allows for interactive, safe, and cost-effective experimental simulations (Kolopajlo, 2017). This medium is designed to illustrate chemical reaction processes, interactions between substances, and laboratory procedures through animations, videos, or web-based applications. The advantages of virtual laboratories include their flexibility of use, widespread accessibility, and the ability to present abstract materials in a more concrete manner.

Research by Ariani & Widodo (2021) shows that virtual laboratories are effective in enhancing students' conceptual understanding and engagement in chemistry learning. This medium also enables students to develop analytical thinking skills through data observation, decision-making, and reflection on simulation results. Furthermore, research by Grieger and Leontyev (2021) demonstrates that the use of infographic projects in green chemistry-based organic laboratories can significantly improve knowledge and responsible skills.

Johnson et al. (2020) found a lack of green chemistry content in standard textbooks, highlighting the need for the preparation of more comprehensive materials. The implementation of green chemistry-based interactive multimedia was also confirmed to be effective by Hadisaputra, Gunawan, and Yustiqvar (2019), while the development of a practicum module by Dewi and Listyarini (2022) proved successful in enhancing students' environmental literacy.

Considering the need to enhance analytical thinking skills, the importance of fostering environmental awareness, and the limited availability of laboratory facilities that align with sustainability principles, the development of a green chemistry-based virtual laboratory medium serves as a strategic solution. This medium is expected to be an effective and interactive learning alternative that is relevant to technological advancements and contemporary demands.

METHODS

Type of Research

This study employs a Research and Development (R&D) approach aimed at producing a learning medium in the form of a green chemistry-based virtual laboratory that is feasible and effective for use in chemistry education. The research design utilized in this study is the 4D development model (Define, Design, Develop, and

Disseminate) developed by Thiagarajan in 1974. The define stage aims to formulate the development objectives and gather initial information regarding the medium to be developed. The information from this stage is used as a foundation for the design stage, which involves designing the green chemistry-based virtual laboratory medium, including determining the format, media, and assessment instruments. The develop stage is conducted to produce a virtual laboratory medium that has undergone an expert validation process. Furthermore, the disseminate stage is carried out to distribute the developed media product to users.

Time and Location of the Research

This research was conducted over a period of six months, from September 2020 to March 2021. The research procedure followed four stages, namely the define, design, develop, and disseminate stages. The define stage was carried out in five Senior High Schools (SMA) located in the Bantul Regency area to identify learning needs and educational problems. Subsequently, the design and develop stages were conducted at the Digilib Library of Universitas Negeri Yogyakarta (UNY) and the Bantul Regional Library, serving as the centers for media development and content design activities. The disseminate stage was then carried out back in the five Senior High Schools in Bantul Regency and its surroundings for readability testing and the limited implementation of the developed virtual laboratory media.

Research Procedure

This research consists of four stages, namely the define, design, develop, and disseminate stages. Broadly speaking, the research procedure can be illustrated in a diagram as shown in Figure 1.

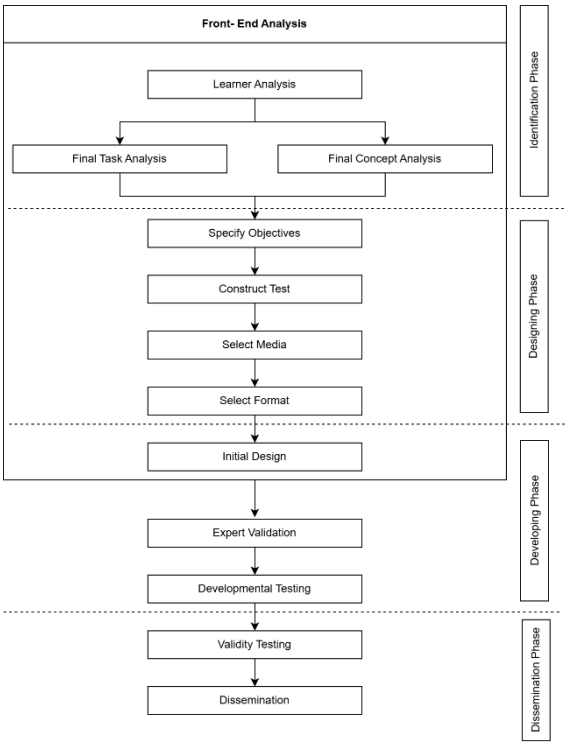

Figure 1. Research Procedure Diagram

The research procedure refers to the 4D development model (Define, Design, Develop, and Disseminate), which consists of several stages as follows:

1. Define

In this stage, an initial analysis is conducted to identify fundamental problems in learning as well as the need for media. Learner analysis is carried out to determine the characteristics of the students, such as academic ability, age, and learning conditions. Subsequently, a task analysis is performed based on core competencies and basic competencies (KI–KD) as well as curriculum documents. In addition, a concept analysis is conducted by compiling a concept map of relevant chemistry topics, followed by the formulation of learning

objectives that serve as the foundation for designing the green chemistry-based virtual laboratory medium.

2. Design

In this stage, the researcher develops test instruments that align with learning indicators, selects media relevant to student characteristics, and determines the presentation format of the media to ensure ease of use in the learning process. The initial product design is then created by taking into account the results of the previous analyses, encompassing content design, layout, and the integration of chemistry topics with green chemistry principles.

3. Develop

The initial design is validated by experts, including both content and media experts, to assess content appropriateness and presentation feasibility. Based on feedback from the validators, product revisions are carried out to produce an improved medium. Following this, a developmental testing is conducted on a limited scale involving chemistry teachers and students to evaluate the feasibility, readability, and effectiveness of the medium.

4. Disseminate

In this stage, the validity of the revised product is re-evaluated by teachers and students to ensure its feasibility for classroom use. The product is then disseminated on a limited basis to chemistry teachers across several Senior High Schools (SMA), and the research findings are published in the form of a scientific paper so that they can be utilized by other researchers and educational practitioners.

Data Collection Techniques

This research employs three main techniques, namely:

1. Documentation

Used during the define stage to gather information regarding the curriculum, core competencies/basic competencies, and tasks that constitute the students' learning workload.

2. Questionnaires

Used to assess the quality and feasibility of the green chemistry-based virtual laboratory medium (by experts, teachers, and students) and to measure the students' environmental awareness attitudes before and after using the medium.

3. Tests

Used to measure the students' analytical thinking skills. The test is in the form of essay questions administered before and after the use of the medium.

Data Collection Instruments

1. Media Feasibility Instrument

The instrument is in the form of a questionnaire based on LORI 1.5 (Learning Object Review Instrument), which encompasses nine assessment aspects.

Table 1. Media Feasibility Grid (Adapted from LORI)

Aspect	Indicator	No. of Items
Content	Content quality	10
	Alignment of objectives	3

Aspect	Indicator	No. of Items
Media	Feedback and adaptation	2
	Motivation	3
	Presentation design	7
Software Media	Interaction usability	3
	Accessibility	5
Managerial &Technical	Reusability	2
	Standards compliance	1

2. Analytical Thinking Skills Instrument

The analytical thinking skills instrument utilizes essay questions. These essay questions will be formulated based on three categories of analytical thinking skills, namely organizing, differentiating, and attributing.

Table 2. Analytical Thinking Skills Test Grid

Aspect	Indicator	No. of Items
Content	Content quality	10
	Alignment of objectives	3
Media	Feedback and adaptation	2
	Motivation	3
	Presentation design	7
Software Media	Interaction usability	3
	Accessibility	5
Managerial and Technical	Reusability	2
	Standards compliance	1

3. Environmental Awareness Instrument

The environmental awareness instrument is in the form of a questionnaire consisting of five aspects, which are subsequently elaborated into several statements. These five aspects of the environmental awareness instrument were adapted from several sources, including Ozden (2008), Kalkan & Demirbas (2014), and Altin et al. (2014).

Table 3. Environmental Awareness Questionnaire Grid

Aspect	No. of Statements	
	+	-
Awareness of environmental issues	5	2
Attitudes toward environmental issues in general	-	3
Carefulness	3	-
Concern	2	-
Level of participation in environmental activities	5	-

Data Analysis Techniques

1. Qualitative Data

Qualitative data analysis in this study was conducted descriptively. Data were obtained from the define stage, in the form of information from documentation results, teachers' opinions, and students' responses regarding learning problems. All of these data were analyzed by reducing information, categorizing it according to themes, and interpreting the meaning of the emerging findings.

Furthermore, during the develop stage, qualitative data were also derived from the feedback provided by experts, teachers, and students regarding the developed media. This feedback was presented narratively to describe the weaknesses, strengths, and areas that required revision.

At this stage, an analysis was conducted on the qualitative data obtained from the reviewers (teachers) and students. The qualitative values were then converted using a Likert scale, resulting in the average data for each component. These scores were subsequently converted into a qualitative product feasibility level based on an ideal conversion.

The quantitative data analysis technique utilized in this research is descriptive statistics. Based on the feasibility assessment through the feasibility test by teachers and the readability test by students, qualitative results and feedback were obtained. These qualitative results were then converted into quantitative values using a Likert scale with criteria according to the following table:

Table 4. Likert Scale Scoring Rules

Category	Score
Very Good (VG)	5
Good (G)	4
Fair (F)	3
Poor (P)	2
Very Poor (VP)	1

Subsequently, the data and scores obtained for each component and their final totals are tabulated, and the average for each assessed aspect is calculated. The obtained average score for each component is then converted into a qualitative product feasibility level using the ideal conversion guidelines (Azwar, 2015: 163), as presented in the following table:

Table 5. Score Conversion Criteria

Score Range	Category
$Mi + 1{,}5\ Si < x \leq Mi + 3\ Si$	Very Good
$Mi + 0{,}5\ Si < x \leq Mi + 1{,}5\ Si$	Good
$Mi - 0{,}5\ Si < x \leq Mi + 0{,}5\ Si$	Fair
$Mi - 1{,}5\ Si < x \leq Mi - 0{,}5\ Si$	Poor
$Mi - 3\ Si \leq x \leq Mi - 1{,}5\ Si$	Very Poor

Subsequently, the overall product value is determined by calculating the average score across all assessment aspects and determining the product feasibility according to the ideal assessment criteria.

2. Quantitative Data

In this study, the validity and reliability of the instruments were evaluated for three types of instruments, namely the media feasibility questionnaire, the analytical thinking skills test, and the environmental awareness questionnaire. Theoretical validity was obtained through expert judgment by expert lecturers, taking into account the suitability of the instrument grids as well as the face validity from the users. Furthermore, empirical validity and reliability were tested on the analytical thinking skills instrument and the environmental awareness questionnaire by involving Senior High School (SMA) students who had studied the chemical equilibrium topic. The analysis utilized the Item Response Theory with the Rasch model through QUEST software, with the item acceptance criteria based on the INFIT MNSQ value (0.77–1.30). The reliability of the instrument was calculated using Cronbach's Alpha, which indicates the level of consistency of the test items.

The environmental awareness instrument is a questionnaire containing 20 statements derived from five main aspects. This questionnaire utilizes a five-point Likert scale, ranging from strongly agree to strongly disagree. The qualitative data from the questionnaire results were then transformed into interval data using the Method of Successive Interval (MSI) with the assistance of Microsoft Excel.

To test the effectiveness of using the green chemistry-based virtual laboratory, the data were analyzed using a paired sample t-test through SPSS software. This test is used to compare the pretest and posttest scores on the variables of analytical thinking skills and environmental awareness measured in the same group of students. Before conducting the paired sample t-test, prerequisite testing was performed on the data in the form of checking the normality of

difference scores using the Shapiro-Wilk test.

In addition, it is necessary to ensure the existence of a linear relationship between variables and the absence of multicollinearity. The Pearson correlation test was used to examine the relationship between analytical thinking skills and environmental awareness, with the interpretation of correlation strength ranging from very weak to very strong.

RESULTS AND DISCUSSION

Product Development

Define Stage

1. Initial Analysis.

This research and development were conducted in Senior High Schools (SMA) in Bantul Regency. The initial analysis stage was carried out by distributing questionnaires to high school chemistry teachers. A total of 9 teachers, all with a minimum of 5 years of teaching experience, completed the questionnaire. The results of the questionnaire analysis indicated that:

- Chemistry teachers experience difficulties in teaching abstract concepts.
- Chemistry teachers encounter difficulties in conducting laboratory practicums during the pandemic due to media limitations.
- The challenges faced by chemistry teachers when conducting laboratory practicums include time constraints and limited equipment.
- Virtual laboratories have not been widely utilized by chemistry teachers due to media constraints and the teachers' limited ability to develop such resources.

Based on these analytical findings, there is a need for media development that can assist chemistry teachers in facilitating practicum-based learning. Students' comprehension is also expected to be higher when they engage in practical work rather than solely relying on theoretical instruction. Furthermore, practicums constitute one of the essential activities for achieving the students' basic competencies.

2. Student Analysis

The subjects of this development research were 11th-grade Senior High School students in Bantul Regency. Based on the students' daily assessment results, the student demographic comprised various cognitive levels, specifically low, intermediate, and high cognitive levels.

The students exhibited active participation in the classroom, driven by the teachers' implementation of learning models that necessitate active student involvement. The majority of students also possessed Android devices and laptops to support their learning processes; thus, they are adequately equipped to operate learning media that require such devices. Consequently, the development efforts focused on a virtual laboratory accessible via Android devices or laptops.

A substantial number of Senior High Schools in Bantul Regency have been designated as Adiwiyata (Green) schools across various levels. Specifically, there are 6 schools recognized at the Regency level, 3 at the Provincial level, 1 at the National level, and 5 established as independent Adiwiyata schools. The designation of

Adiwiyata schools extends beyond physical infrastructure to include pedagogical transformations. For instance, the instructional process incorporates environmentally based media. In addition to instructional changes, Adiwiyata schools cultivate a distinct eco-friendly school culture for all members of the school community. Therefore, the developed virtual laboratory is designed as a green chemistry-based virtual laboratory.

3. Task Analysis

The task analysis conducted aims to identify the skills required by students in accordance with the applicable curriculum. Higher-order thinking skills are among the competencies that students must possess. Higher-order thinking skills encompass analyzing, evaluating, and creating (Anderson et al., 2001). The ability to analyze is divided into three components, namely differentiating, organizing, and attributing. Analytical thinking skills can also be developed through environmental education integrated into the learning process. This is because cognitive ability is positively correlated with environmental awareness (Salahodjaev, 2018). Therefore, both of these aspects can be imparted to students simultaneously. Analytical thinking skills and environmental awareness can be provided to students concurrently by bringing up news regarding environmental issues (Bozoglu et al., 2016). Hence, the integration between analytical thinking skills and environmental awareness in learning is highly necessary for students.

2. Concept Analysis

In the concept analysis step, a literature study of sub-concepts regarding the chemical equilibrium topic is determined. The analysis is conducted on facts, concepts, principles, and theories. The concept analysis is illustrated in Figure 2.

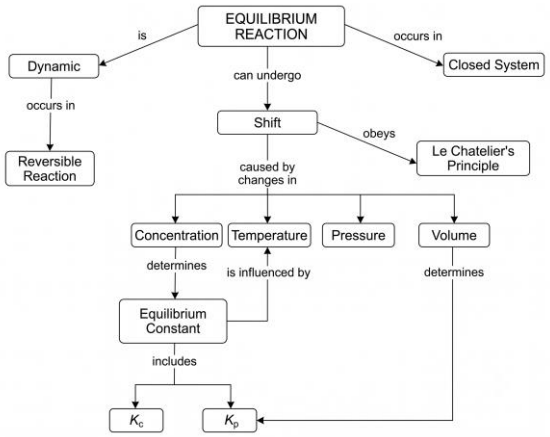

Figure 2. Concept of Chemical Equilibrium

1. Specification of Learning Objectives

The developed product is a green chemistry-based virtual laboratory for the chemical equilibrium topic. In this stage, the formulation of learning objectives to be achieved is oriented towards analytical thinking skills and environmental awareness in basic competencies 3.8, 3.9, 4.8, and 4.9, in accordance with the 2013 curriculum under special conditions. This aims to delimit the virtual laboratory development product so that it does not deviate from the initial objectives.

Design Stage

1. Media Preparation

The preparation of the virtual laboratory begins with creating a flowchart and a storyboard, which serve as references in developing the green chemistry-based virtual laboratory medium. The flowchart contains the layout design used to provide a clear sequence for the components within the green chemistry-based virtual laboratory. Meanwhile, the storyboard in this research functions as a detailed overview of the content, images, videos, and design of the virtual laboratory.

The next stage is the collection of material scripts, practicum guides, images, audio, and practice questions. The virtual laboratory will contain materials on chemical equilibrium, chemical equilibrium practicums, and practice questions. The

materials and practicums integrated into this virtual laboratory are modified based on green chemistry principles to support the students' analytical thinking skills and environmental awareness. Subsequently, all of these components will be assembled using computer software.

2. Test Selection

The test analysis aims to determine the type of test required for the students to achieve the Core Competencies (KI) and Basic Competencies (KD). The selected test format is an essay test. This type of test is aligned with the indicators of analytical thinking skills and environmental awareness. The results of the students' work on essay questions yield higher consistency for each item compared to the results of a multiple-choice test. Furthermore, the essay test format provides students with the freedom to reason, thereby revealing the students' complex thinking abilities (Susongko, 2010).

This essay test consists of two types, namely a pretest and a posttest. The pretest is administered to the students to assess their baseline abilities prior to learning, whereas the posttest aims to evaluate the students' abilities after learning using the green chemistry-based virtual laboratory.

Develop Stage

The develop stage aims to produce a revised final product in the form of a green chemistry-based virtual laboratory. The trials conducted on this virtual laboratory encompass usability tests and readability tests. Meanwhile, the instruments utilized in this research are the analytical thinking skills essay test and the environmental awareness questionnaire. Both instruments have undergone content validation through expert judgment by receiving feedback, which subsequently served as the basis for their revision. Both instruments have also undergone empirical validation.

Another supplementary material in this research is the Lesson Plan (Rencana Pelaksanaan Pembelajaran/RPP). The Lesson Plan was designed based on the 2013 curriculum under special conditions. The learning activities are conducted utilizing the Problem-Based Learning (PBL) model. This is reflected in the Student Worksheets (Lembar Kerja Peserta Didik/LKPD) provided to the students. The PBL model consists of 6 stages: identifying the problem, formulating the problem, formulating a hypothesis, conducting investigations, analyzing data, and drawing conclusions. The Lesson Plan and Student Worksheets can be found in Appendices 1 and 2.

Before the analytical thinking skills test instrument was deployed in this research, empirical testing was conducted. The pretest contains the same number of questions as the posttest, totaling 21 items. However, only 20 pretest items and 20 posttest items were deemed valid after conducting the empirical test and data analysis using the QUEST program. Therefore, the number of questions utilized in this research is 20 pretest items and 20 posttest items. The analytical thinking skills test questions can be found in Appendix 5. Meanwhile, for the environmental awareness questionnaire, which initially consisted of 21 statements, 20 valid statements remained to be used in the research following empirical testing and data analysis.

This research was conducted to develop a green chemistry-based virtual laboratory on the chemical equilibrium topic. The creation of the virtual laboratory was executed using Adobe Illustrator and Adobe Flash software.

Disseminate Stage

The disseminate stage of this green chemistry-based virtual laboratory was carried out by providing the application to several chemistry teachers in Senior High Schools across Bantul Regency.

Product Feasibility Assessment Data

The trials of this virtual laboratory were conducted through several sequential stages, namely content validation by expert judgment, usability assessment by chemistry teachers, readability testing by students, and effectiveness testing of the green chemistry-based virtual laboratory.

1. Validation by Expert Judgment

The content of this green chemistry-based virtual laboratory has been validated by two experts (expert judgment). In general, the results of the product review indicated that revisions were necessary. Once the revisions were implemented, the product could subsequently be utilized for the research. The product review results took the form of revision suggestions derived from the expert judgment.

2. Product Usability Assessment by Chemistry Educators

The feasibility of the green chemistry-based virtual laboratory was assessed by 9 11th-grade Senior High School chemistry teachers in Bantul Regency. The assessing chemistry teachers met specific criteria, such as possessing more than 5 years of teaching experience, teaching at an Adiwiyata (Green) school, and having implemented student-centered learning. The assessment was conducted across four aspects, namely content, media, software media, and managerial and technical aspects.

Table 6. Product Usability Assessment by Chemistry Educators

Aspect	Average	(%)	Category
Content	4.42	88%	Very Good
Media	4.29	86%	Very Good
Software Media	4.4	88%	Very Good
Managerial and Technical	4.67	93%	Very Good
Average	4.445	89%	Very Good

Based on Table 6, it can be observed that all four aspects of the green chemistry-based virtual laboratory fall into the "very good" category, indicating that the product is feasible for use as a virtual laboratory in schools. The lowest average score is found in the media aspect, which is 4.29 with a percentage of 86%, while the highest average score is in the managerial and technical aspect, which is 4.67 with a percentage of 93%. However, the difference between the two is relatively small; thus, they still remain within the same category of "very good."

3. Product Readability Assessment by Students

The readability assessment of the green chemistry-based virtual laboratory was conducted on 36 students at SMAN 2 Bantul. The students selected as the sample were those who had completed the chemical equilibrium topic and possessed varying cognitive levels, encompassing high, intermediate, and low cognitive levels. This aimed to ensure that the virtual laboratory medium could be well comprehended by all students. The readability assessment encompassed two aspects, namely the media and visual appearance aspects.

Table 7. Product Readability Assessment by Students

Aspect	Average Score	Percentage	Category
Media	4.32	86.40%	Very Good
Visual Appearance	4.07	81.50%	Very Good
Average	4.2	84%	Very Good

Based on Table 7, it can be observed that both aspects fall into the very good category with an average score of 4.20 and a percentage of 84%. Based on the readability assessment by the students, the product is categorized as very good; thus, it is deemed feasible to be utilized as a learning medium in the instructional process.

Field Trial Results

The analytical thinking skills test was administered to two experimental classes prior to and following the implementation of learning utilizing the green chemistry-based virtual laboratory. The analytical thinking skills test employed comprised 20 items. The pretest and posttest shared an identical test grid; consequently, both sets of questions possessed equivalent weighting.

Table 8. Summary of Analytical Thinking Skills Scores

Score	Pre-test	Post-test
Highest	68	98
Lowest	31	69
Average	49.93	85.03

The environmental awareness questionnaire was administered to the two experimental classes before and after the learning activities utilizing the green chemistry-based virtual laboratory.

The summary of the environmental awareness scores can be seen in Table 9 as follows.

Table 11. Summary of Environmental Awareness Questionnaire Scores

Score	Pre-test	Post-test
Highest	77.69	80.32
Lowest	50.09	45.8
Average	62.82	63.46

Data Analysis Results

Before conducting the hypothesis testing, the research data were first tested through several prerequisite tests. The test results indicated that the data satisfied the analytical assumptions, namely: (1) there are two dependent variables, comprising analytical thinking skills and environmental awareness, which were measured on an interval scale; (2) the independent variable is the use of the green chemistry-based virtual laboratory, categorized into two conditions (pretest and posttest); (3) the research sample consisted of 67 students who were measured twice (pretest and posttest), thus establishing paired data (dependent samples); (4) there were neither univariate nor multivariate outliers present; (5) the normality test was conducted on the difference scores (posttest–pretest) utilizing the Shapiro-Wilk test, yielding a significance value > 0.05, thereby satisfying the normality assumption; (6) the data exhibited homogeneity based on Box's M test ($p = 0.802 > 0.05$); (7) there was a linear relationship between the dependent variables, with a significance value of 0.610 (> 0.05); and (8) multicollinearity did not occur, as indicated by a tolerance value of 0.998 and a VIF of 1.00.

Table 12. Data Analysis Results

Test	Results	Conclusion
Normality (Shapiro-Wilk)	Sig. > 0.05 (Analytical pre = 0.772; post = 0.151; Environmental pre = 0.439; post = 0.586)	Data are normally distributed
Homogeneity (Box's M)	Value = 1.013; Sig. = 0.802 (> 0.05)	Data are homogeneous
Outlier	No univariate or multivariate outliers	Data satisfy the assumptions
Linearity	Sig. = 0.610 (> 0.05)	Linear relationship between variables is satisfied
Multicollinearity	Tolerance = 0.998; VIF = 1.00	No multicollinearity
Pearson Correlation	r = 0.040 (very weak)	Further analysis using Paired T-test

Test	Results	Conclusion
Paired Sample T-test (Analytical)	Sig. $p < 0.001$	Significant difference exists (increased)
Paired Sample T-test (Environmental)	Sig. = 0.494 (> 0.05)	No significant difference
Effect Size (Cohen's d)	d value = 3.34	Very large
Gain Score	0.70 ($g \geq 0.70$)	High

Pearson correlation analysis indicated a very weak relationship ($r = 0.04$) between analytical thinking skills and environmental awareness, prompting the use of a Paired Sample T-test for hypothesis testing. The results revealed that the green chemistry-based virtual laboratory significantly improved analytical thinking ($p < 0.001$) with a very large effect size (Cohen's $d = 3.34$) and a high N-gain (0.70). However, it did not produce a significant difference in environmental awareness ($p = 0.494 > 0.05$).

Discussion

1. Characteristics of the Green Chemistry-Based Virtual Laboratory

Developed using Adobe Illustrator and Flash, this virtual laboratory addresses the limitations of online learning by providing a safe, simulative practicum experience. It features four chemical equilibrium experiments that integrate green chemistry principles, such as waste prevention and energy efficiency. This approach fosters independent digital exploration and higher-order thinking skills, corroborating previous research on the efficacy of environmentally-based practicums (Redhana, 2017).

2. Feasibility of the Virtual Laboratory

Following expert validation, the product was deemed highly feasible, achieving "very good" categories in both the teacher usability assessment (89%) and the student readability test (84%). Furthermore, students found the media highly attractive and motivating. Consistent with prior literature, this virtual platform provides a safe, cost-effective, and visually engaging alternative that enhances both motivation and conceptual understanding.

3. Implementation of the Virtual Laboratory

The media was implemented among 67 students using a Problem-Based Learning (PBL) model across four hybrid meetings. The teacher's role as a facilitator was crucial in guiding collaborative discussions and mitigating technical constraints.a. Differences in Students' Analytical Thinking SkillsThe average analytical thinking score significantly increased from 49.93 to 85.03 ($p < 0.001$). This confirms the virtual laboratory's robust effectiveness in fostering higher-order thinking. All analytical aspects improved, with the "attributing" aspect showing the most substantial gain, demonstrating the success of PBL-based group analysis.b. Differences in Students' Environmental AwarenessConversely, environmental awareness showed a marginal, non-significant increase from 62.82 to 63.46 ($p > 0.05$). This limited impact is attributed to the students' already high baseline awareness, the brief intervention period, and the simulative nature of the media. These findings align with prior studies indicating that translating awareness into actual environmental participation requires continuous, real-world educational programs rather than short-term simulations.

CONCLUSION

This study successfully developed a green chemistry-based virtual laboratory for the chemical equilibrium topic, which was validated as highly feasible for instructional use. Efficacy trials demonstrated that the media significantly enhanced students' analytical thinking skills, evidenced by substantial score improvements, a large effect size, and a high N-gain. Conversely, the improvement in students' environmental awareness was not statistically significant, indicating that fostering such consciousness requires more continuous and contextual pedagogical approaches. Ultimately, this virtual laboratory is highly effective in developing analytical thinking and serves as a safe, interactive, and sustainable alternative for chemistry education.

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