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Development of Green Chemistry-Based Pratical Guidebook for Chemistry Education in Senior High School

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ABSTRACT

This study aims to develop valid, practical, and effective green chemistry-based chemistry laboratory instructions to support chemistry learning at Muarasipongi 1 Public High School. The method used is Research and Development (R&D) with a 4D model limited to the Develop stage due to time constraints. The research subjects consisted of 23 students in class XI-1 with purposive sampling technique. The research object was a green chemistry-based chemistry practicum manual. The research instruments included expert validation sheets (material, media, and language), practicality questionnaires, and learning outcome tests. Data analysis using descriptive quantitative analysis to assess the validity, practicality, and effectiveness of the product through percentages, N-Gain, and student responses. The results of expert validation showed that the product was highly valid, with an average percentage of 87.5%. Practicality tests conducted by teachers and students showed that the product was highly practical, with percentages of 89% and 91%, respectively. Effectiveness tests based on student learning outcomes and scientific attitudes showed a percentage of 68% and were classified as highly effective. These practical guidelines integrate green chemistry principles, such as waste prevention and the use of safe materials. Thus, this product is suitable for use as a support for environmentally friendly and contextual chemistry learning at the senior high school level.

INTRODUCTION

Chemistry is an abstract science, and a scientific process is needed to make it more concrete. One way to carry out this scientific process is through experimental learning activities. Experimental learning can be done by conducting practical methods on the material being taught (Enawaty, 2021). Practical work is a form of process skills approach that can train students' abilities. After a concept has been studied by students, they can prove the truth of the concept by conducting practical activities. Through practical activities, students gain direct experience as a result of meaningful learning (Emda, 2022).

Practical activities have various benefits, but they also have several obstacles. One of them is waste management. To date, many chemistry practical activities in schools use hazardous materials, and in practice, there has been no specific attention paid to the waste produced (Setianingsih, 2023). This will certainly have an impact on environmental and ecosystem damage. In addition, not all schools have complete chemical materials that can be used for every practical activity, and The lack of structured chemistry lab manuals based on green chemistry at Muarasipongi State High School 1. Lab activities conducted thus far still rely on verbal

explanations from teachers and simple worksheets, necessitating the development of lab manuals that meet the chemistry learning needs of the school.

Practical work is a way of presenting a lesson through experiments carried out by students. Students actually experience and prove for themselves what they have learned. The practicum method provides students with the opportunity to experience or do things themselves, follow a process, observe an object, analyze data, and draw conclusions about a situation or process. In addition, practicums can also provide students with learning experiences in conducting specific experiments (Amaliah dkk., 2023) These chemistry practicums are important for students in chemistry learning in order to gain knowledge based on the practicum activities that have been carried out.

Laboratories can be used as facilities for conducting experiments, research, or scientific studies by lecturers, researchers, or students in science education, particularly in chemistry education. The functions of a laboratory are to complement lessons by showing that theory and practice are two sides of the same coin, to provide students with scientific work skills, to improve their skills in using equipment and practical manuals, and to increase students' curiosity about experiments (Setiyani, 2023).One of the functions of a laboratory is to develop students' performance skills during experiments.

Green chemistry is an innovative chemical technology concept that reduces the use and production of hazardous chemicals, as well as the manufacture and use of chemical products (Herliani dkk., 2025) The objectives of green chemistry technology are to reduce waste, minimize the use of hazardous materials, reduce the use of energy and non-renewable natural resources, and maximize the use of materials in chemical processes. By using practical methods that utilize green chemistry, learning will be directed towards a concrete learning process and discussions with friends so that new ideas, concepts, or concepts can be obtained (Djangi dkk., 2024).

Green chemistry is a concept that encourages the design of products or processes to reduce or eliminate the use of hazardous substances in production (Harahap dkk., 2024). Aspects of green chemistry include minimizing hazardous substances, using non-toxic reagents, using renewable resources, and using environmentally friendly and recyclable solvents. Green chemistry aims to improve chemical processes and production that are environmentally friendly and in line with sustainable development (Purwanti dkk., 2023). The application of green chemistry is essential because chemical production consumes a large amount of energy, is inefficient, involves toxic substances, and produces hazardous waste. Therefore, green chemists work to ensure that the chemical products produced have only minimal harmful effects on human health and the environment. One way to do this is by prioritizing the use of alternative and renewable materials, including utilizing agricultural waste or biomass (Zuin dkk., 2021)

Considering the significant role of laboratories in chemistry education, teachers are required to be highly creative, because the role of laboratories is no longer limited to utilizing the tools and materials available in the laboratory, but also includes designing and developing alternative laboratory activities or practicums that are oriented towards green chemistry concepts (Freese dkk., 2024). Steps that can be taken to apply the principles of green chemistry in practical activities are to develop practical guides based on green chemistry.

One solution to minimize waste from practical work and improve workplace safety in laboratories is the application of green chemistry principles. Green chemistry is an innovative chemical technology concept that reduces the use and production of hazardous chemicals, as well as the manufacture and use of chemical products. The objectives of green chemistry technology are to reduce waste, minimize the use of hazardous materials, reduce the use of energy and non-renewable natural resources, and maximize the use of materials in chemical processes. Green chemistry has emerged as a revolutionary approach, advocating the design of

chemical products and processes that reduce or eliminate the use and generation of hazardous substances (Sembiring dkk., 2022).

There are several principles underlying green chemistry, such as preventing the formation of toxic waste is better than treating or cleaning up the waste. (1) Economizing atoms in designing synthesis methods, (2) Synthesizing chemicals that are not or less harmful to human health and the environment, (3) Designing safer chemical products, even if their toxicity is reduced but their function remains effective, and (4) Using safer and non-hazardous solvents and supporting materials (Eva Fadillah, 2022)

Research by (Ilma dkk., 2022) developed green chemistry-based electronic laboratory guidelines on acid-base material using the Learning Cycle-7E model and showed valid and practical results. However, this research is still limited to one material and one learning model, so it does not accommodate the application of more flexible green chemistry laboratory guidelines in accordance with diverse school conditions. Furthermore, research by (Adela dkk., 2022) developed green chemistry-based practicum guidelines on the material of the effect of catalysts on reaction rates and proved to be valid, practical, and effective. However, this research is still in a limited context and has not been specifically directed at implementation in secondary schools with certain characteristics and resource limitations.

Meanwhile, research (Fanesa dkk., 2021) focused on developing integrated independent practical modules based on green chemistry on the subject of acids and bases, but emphasized the learning module aspect rather than practical instructions used directly in the laboratory. The study by (Ayuningtiyas dkk., 2022) developed electronic green chemistry-based practical instructions on reaction rate material at SMA Negeri 8 Semarang and received a very good response, but its application is still limited to one school with specific conditions. Thus, the four studies have not specifically developed green chemistry-based chemistry practical guidelines tailored to the conditions, needs, and characteristics of chemistry learning at SMA Negeri 1 Muarasipongi, making this research important to conduct.

Previous studies have shown that practical activities are beneficial. These include improving students' understanding of chemistry concepts, improving their ability to gather information, increasing their motivation to learn, and making them more open, creative, critical, and skilled. Students will be better able to understand and connect learning content that is more relevant to their environment and provide greater educational meaning when presented in the form of contextual challenges that are often encountered in everyday life.

Based on the above description, it is necessary to develop green chemistry-based chemistry laboratory instructions. It is hoped that this will encourage students to discover new knowledge through environmentally friendly experiments. Therefore, the researcher is interested in developing the title “Development of Green Chemistry-Based Chemistry Laboratory Manual in Senior High School”.

METHODS

Research Design

The type of research used was R&D (Research and Development) aimed at producing and testing the effectiveness of the product, namely a green chemistry-based practical instruction book. The development model applied was the 4D model (Define, Design, Development, Disseminate)(Sugiyono, 2008). This model was chosen because it was in line with the structured and systematic stages of product development, starting from needs analysis to the dissemination of the final product. The development model uses the 4D design according to (Thiagarajan dkk., 1974) which is presented as follows.

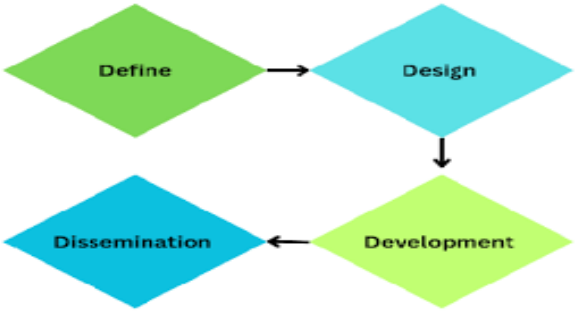


Figure 1. 4D Development Research Model (Thiagarajan dkk., 1974)

Research Target

The targets of this study include several parties and objects directly involved in the product development process. The main target of the study is 23 students in class XI-1 of Muarasipongi 1 Public High School in the 2024/2025 academic year as subjects for testing the use of practical instructions. In addition, chemistry teachers at Muarasipongi 1 Public High School are also the targets of the study in testing the practicality of the product. The product targeted for development is a green chemistry-based chemistry practical guidebook on thermochemistry, reaction rates, chemical equilibrium, and acids and bases. This research also involves subject matter experts, media experts, and language experts as parties who assess the validity of the developed product.

Research Data

The research data collected in this study consisted of data on the validity, practicality, and effectiveness of the product. Validity data were obtained from the results of expert validators' assessments of the material, media, and language aspects of the green chemistry-based practicum manual. Practicality data were obtained through questionnaires for teachers and students to determine the ease of use, clarity of content, and feasibility of the practicum instructions in learning. Furthermore, effectiveness data was obtained from student learning outcomes measured through pre-tests and post-tests and analyzed using the N-Gain test to determine the increase in learning outcomes (Rangkuti, 2016). In addition, data on students' scientific attitudes during practical activities was also collected as supporting data to assess the overall effectiveness of the product.

Research Instruments

The research instruments used in this study included expert validation sheets, practicality questionnaires, learning outcome tests, and scientific attitude observation sheets. The expert validation sheets were used to assess the feasibility of the practicum manual in terms of content, media display, language use, and conformity with green chemistry principles. The practicability questionnaire was used to collect data on teachers' and students' responses to the ease of use, attractiveness, and usefulness of the product. The learning outcome test, in the form of a pretest and posttest, was used to measure the increase in students' understanding after using the practicum manual. In addition, the scientific attitude observation sheet was used to assess students' attitudes during practicum activities, such as honesty, accuracy, responsibility, and cooperation (Silitonga, 2013).

Data Analysis

The validation stage carried out by the validator covers two aspects, namely content validity and construct validity. The data values provided by the validator through the validation sheet will then be analyzed using calculations from relevant theories. The calculation formula for analyzing validity is as follows:

$$Vah = \frac{Tse}{Tsh} \times 100\%$$

Description:
Vah = Validity percentage
Tse = Final score attained
Tsh = The highest score

Then, the percentage results of the validity of the Chemistry based Practical Guidebook obtained from the validators were categorized based on the table below.

Table 1. Criteria for Green Chemistry based Practical Guidebook

Validity Percentage (%)	Category
81 - 100	Very valid
61 - 80	Valid
41 - 60	Sufficiently Valid
21 - 40	Less valid
0 - 20	Not valid

The feasibility assessment results of the Green Chemistry based Practical Guidebook were based on the activity implementation assessment sheet evaluated by three observers through observation during the learning activities and calculated using the following equation:

$$P = \frac{Tse}{Tsh} \times 100\%$$

Description:
P = Percentage of practicality
Tse = Final score attained
Tsh = The highest score

Then the percentage results of the practicability of using the Chemistry based Practical Guidebook obtained will then be categorized based on the criteria as shown in the table below.

Table 2. Criteria Pratically for Green Chemistry based Practical Guidebook

Practicality Percentage (%)	Category
81 - 100	Very Practical
61 - 80	Practical
41 - 60	Quite Practical
21 - 40	Less Practical
0 – 20	Not practical

The improvement in green chemistry principles, measured through pretest and posttest results, shows the effectiveness of the analyzed Green Chemistry based Practical Guidebook by applying the N-Gain calculation as follows:

$$\text{N} - \text{Gain Score} = \frac{\text{Postest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}} \times 100\%$$

The results of the N-Gain score obtained are then normalized The success of a product is determined based on the N-Gain (%) value obtained from comparing pretest and posttest scores. A product is categorized as highly successful if the N-Gain value is more than 71%, moderately successful if the N-Gain value is between 31% and 70%, and lowly successful if the N-Gain value is less than 30%. These criteria are used to assess the effectiveness of the developed product.and categorized according to the criteria in the following table.

Table 3. N-Gain Score Criteria

N-Gain Score	Category
N-Gain > 71	High
31 < 70	Medium
N-Gain < 30	Low

The results of the effectiveness of the Green Chemistry based Practical Guidebook obtained from student responses on a questionnaire sheet with assessment indicators including appearance, content/material, and language. The student response questionnaire will then be analyzed using a Likert scale with a total scale choice of 4 points through the following formula:

$$\text{Precentage of student response (R)} = \frac{\text{Total score obtained}}{\text{Total maximum score}} \times 100\%$$

The results of the student response questionnaire scores obtained are then categorized based on the table below:

Table 4. Student Score Criteria

Percentage (%)	Category
81 - 100	Very Positive
61 - 80	Positive
41 - 60	Sufficiently positive
25 - 40	Not Positive

RESULTS AND DISCUSSION

This study resulted in a green chemistry-based chemistry practicum guide designed to support chemistry learning at senior high school in Muarasipongi. The development process aimed to produce a practicum guide that meets the criteria of validity, practicality, and effectiveness in accordance with the principles of green chemistry. The research was conducted on students of class XI-1 during the 2024/2025 academic year using a Research and Development (R&D) approach with the 4D model, consisting of the Define, Design, Develop, and Disseminate stages.

a. Define Stage

At the design stage, the structure and content of the practicum guide were planned based on the results of the define stage. The practicum guide was designed in printed book format with systematic components, including laboratory rules, safety symbols, practicum objectives, theoretical background, tools and materials, experimental procedures, observation sheets, green chemistry principles, and practicum report formats.

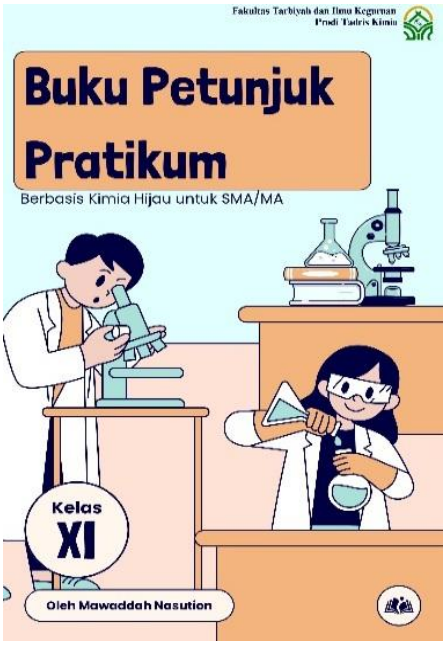
The analysis of the students' front end revealed that the facilities available at the Indonesian Institute High School were complete and adequate for conducting practical work, the students' independent attitude when conducting practical work, and the results of the student needs questionnaire, as shown in the following figure.

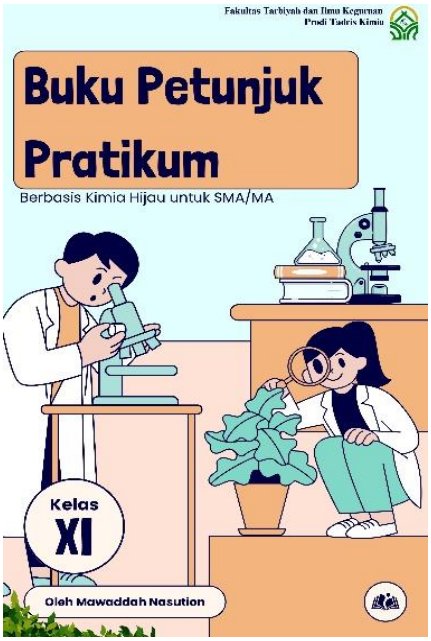
Figure 2. Currently Conducting Practical Work

In addition to the student needs questionnaire, the researchers also interviewed students to obtain clearer information about the implementation of chemistry practicals at school. Each practicum activity was designed by integrating green chemistry principles such as waste prevention, the use of safer chemicals, energy efficiency, and minimizing hazardous substances. The experiments were adjusted to the available laboratory facilities at senior high school in Muarasipongi. This design aimed to ensure that the practicum guide is not only aligned with curriculum demands but also practical and environmentally friendly. The clear structure and simple language were intended to help students conduct experiments independently and safely (Natania dkk., 2025).

b. Design Stage

At this stage, text and images are integrated systematically while still paying attention to the layout so that it is not too dense, but still informative and comfortable to read. The preparation of the Green Chemistry based Practical Guidebook involves several parts, including instructions for use, learning outcomes, learning objectives, concept maps, table of contents, material descriptions, and student activities that have been adjusted to science literacy indicators by integrating Green Chemistry aspects.





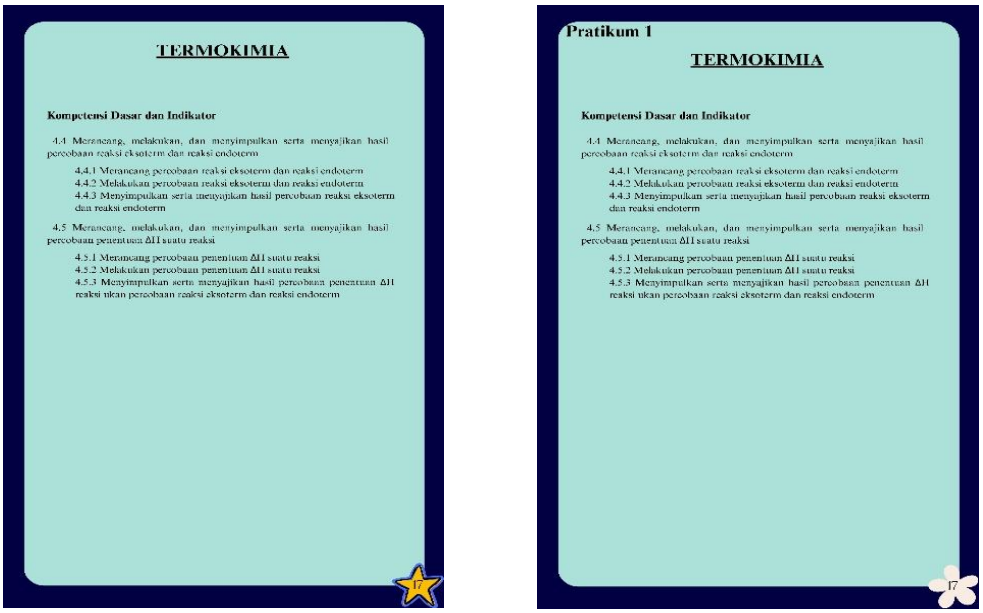


Figure 3. Design Green Chemistry based Practical Guidebook

Guidebook will be uploaded online and published so that users can obtain a link to access it. Then, the completed Green Chemistry-based Practical Guidebook will be uploaded online and published so that it will have a link to access the Green Chemistry-based Practical Guidebook. Research conducted by (Ismail & Hasanah, 2024) states that the Canva application was chosen as the medium for creating Flip books for Basic Chemistry Practicum Guides because it is capable of displaying text, images, videos, illustrations, music, and animations that can help improve students' understanding of learning materials. Additionally, electronic learning media makes the content presented more visually appealing and provides users with the convenience of being able to access it anywhere and anytime.

The selection of digital media in the development of this chemistry laboratory manual aims to improve accessibility, so that students can access the laboratory manual anytime and anywhere without relying on print media. In addition, the use of digital media is designed to support independent learning, as students can learn laboratory procedures, chemistry concepts, and work steps independently before and after the laboratory activities take place. The selection of digital media is also tailored to the digital literacy level of high school students, so it is expected to increase student engagement and the effectiveness of chemistry learning at Muarasipongi 1 Public High School.

c. Develop Stage

Overall, the percentage of media expert validation from Table 5 is 89.88% in the “highly valid” category. The percentage comes from the accumulation of material, media, and language aspects. The material sub-aspect received 88% with “highly valid”. In terms of clarity, the cover, illustrations, and design appeal are appropriate. In line with the statement (Putra et al., 2023, p. 503), the cover of a chemistry practicum manual is the face of the manual, serving as the first impression to attract students' attention. In relation to (Narestuti & Nurjanah, 2021, p. 312), the suitability of the illustrations on the cover and throughout the chemistry practicum manual helps students to represent the specific forms or examples of the material being discussed.

Table 5. Overall Validation Results Data

Validity	Percentage	Category
Content Validator	88%	Very Valid
Media Validator	90%	Very Valid
Language Validator	91,66%	Very Valid
Overall Average	89,88%	Very Valid

Media Expert Validation

Validation by media experts shows that the green chemistry-based practical guide developed meets the criteria for visual design, layout consistency, and media feasibility. The validation score obtained falls into the highly valid category, indicating that the media is attractive and easy to use. Therefore, this practical guide is suitable for supporting chemistry learning activities.

Table 6. Results of Expert Media Validator Assessment of Green Chemistry-based Practical Guidebook

Aspect	Num	Indicator	Expert Score	Max Score	P (%)	Criteria
Illustration/ Image	1	Images support conceptual understanding	4	4	100	Very Valid
	2	Harmonious image layout and clear functionality	4	4	100	Very Valid
Color Selection	3	Do not use too many color combinations.	4	4	100	Very Valid
	4	Shape, color, size, proportion, objects according to reality	3	4	75	Valid
Layout	5	Text, images, and tables are neatly arranged	4	4	100	Very Valid
	6	Placement of layout elements based on consistent patterns	3	4	75	Valid
Readability	7	Font size, font type, spacing, and readability	4	4	100	Very Valid
	8	The placement of decorations/illustrations as backgrounds does not interfere with the title, text, or page numbers.	4	4	100	Very Valid
Practical Instruction Format Compliance	9	Systematic format, including title, objectives, tools, materials, and procedures for data results	3	4	75	Very Valid
	10	Accurate and proportional shape in accordance with reality	4	4	100	Very Valid
Total Number of Items			**33**	**40**	**82,5**	**Very Valid**

Based on Table 6, the percentage obtained from subject matter experts was 82.5%, which is in the highly valid category and ready to be tested in the next stage. The learning media development product is in softcopy form, namely a chemistry practicum manual specifically on acid-base material.

Subject Matter Expert Validation

Subject matter expert validation shows that the content accuracy, concept relevance, and alignment with learning objectives are well fulfilled. The practicum guide obtained a very valid category, indicating that the material is scientifically correct and appropriate for high school chemistry. Thus, the content is suitable for use in chemistry practicum learning.

Table 7. Results of Expert Subject Matter Validator Assessment of Green Chemistry-based Practical Guidebook

Num	Indicator	Expert Score	Max Score	P (%)	Criteria
Material Suitability Aspects					
1	The practicum complies with the principles of green chemistry (efficient, safe, minimal waste).	3	4	75	Valid
2	Clarity of practical objectives	3	4	75	Valid
3	Correct use of chemical symbols/terms/formulas	3	4	75	Valid
Aspects of Suitability with the Curriculum					
4	Material in line with basic high school competencies	4	4	100	Very Valid
Observation Point					
5	Accurate scientific information and concepts	3	4	75	Valid
6	The observation results format is easy to understand.	3	4	75	Valid
Green Chemistry Aspects					
7	There are green chemistry lab materials.	3	4	75	Valid
8	The materials used in practical activities are safe for students.	4	4	100	Very Valid
9	The work procedures used are safe for students.	4	4	100	Very Valid
Difficulty Level Aspect					
10	The concepts presented are correct with up-to-date references.	3	4	75	Valid
	Total Number of Items	**33**	**40**	**82,5**	**Very Valid**

Based on Table 7, the percentage obtained from Subject matter was 82.5%, which is in the highly valid category and ready to be tested in the next stage.

Language Matter Expert Validation

Learning media for chemistry practical work manuals, specifically on the subject of acids and bases. Based on the percentage obtained from language experts, 77.5% was categorized as valid and ready to be tested in the next stage, as shown in Table 7 below

Table 8. Results of Language Expert ValidationValidator Assessment of Green Chemistry-based Practical Guidebook

Num	Indicator	Expert Score	Max Score	P (%)	Criteria
Aspects of Sentence Clarity					
1	Sentences that are unambiguous and easy to understand	3	4	75	Valid
2	Representing the message conveyed	3	4	75	Valid
Compliance with PUEBI Spelling Rules					
4	Proper use of punctuation, capitalization, and standard vocabulary	4	4	100	Very Valid
5	The punctuation used is clear.	4	4	100	Very Valid

Num	Indicator	Expert Score	Max Score	P (%)	Criteria
Aspects of Paragraph Integration					
6	Logical and coherent relationships between sentences	3	4	75	Valid
Aspects of Chemical Term Consistency					
7	Scientific terms according to context and standards	3	4	75	Valid
Language Flexibility Aspects					
8	Communicative language appropriate for high school students	4	4	100	Very Valid
9	Communicated in an engaging manner	3	4	75	Valid
10	Accurate and effective language delivery	4	4	100	Very Valid
Amount		**31**	**40**	**77,5**	**Valid**

Based on the average responses of teachers and students regarding the use of chemistry lab manuals, the practicality of the media can be seen as follows:

Table 9. Average Practicality Score of Green Chemistry-based Practical Guidebook

Response	Percentage of Practicality
Teacher Responses	88%
Student Responses	91,2%
Average	**89,6 %**

d. Desseminate Stage

The disseminate stage in this study was limited due to time constraints. However, the final version of the green chemistry-based practicum guide was introduced to chemistry teachers at senior high school Muarasipongi as a reference for future practicum activities. Teachers responded positively and considered the practicum guide useful as an alternative teaching material that supports environmentally friendly laboratory practices. Although large scale dissemination was not conducted, the results indicate that the practicum guide has the potential to be implemented more broadly in chemistry learning, particularly in schools with limited laboratory facilities and concerns about chemical safety and environmental impact. The strengths and weaknesses of the chemistry lab manual according to subject matter experts, media experts, and language experts are as follows:

Table 10. Strengths and Weaknesses of the Green Chemistry-based Practical Guidebook According to Validators

Validation	Advantages	Weakness
Subject Matter Expert	The material in this chemistry lab manual has been arranged in a logical sequence and is in accordance with the applicable curriculum.	Some parts of the material are not in-depth enough, especially the core concepts, which should be explained more clearly.
Media Expert	The visual display is very attractive and colorful.	Some panels contain too much text, which can make them difficult to read
Linguist	The language used is quite communicative and appropriate for the characteristics of the students	There are still some spelling and punctuation errors.

The results of this research indicate that the green chemistry-based practicum guide developed using the 4D model (Define, Design, Develop, Disseminate) successfully meets the criteria of validity, practicality, and effectiveness. The Define stage revealed specific needs within chemistry practicum instruction, where conventional laboratory guides often lack environmental considerations and student engagement. Previous research similarly highlights the importance of integrating green chemistry principles in laboratory design to reduce

hazardous waste and align with sustainable curriculum goals, underscoring the relevance of this study's needs analysis approach (Widyastuti, 2022).

At the Design stage, the practicum guide was structured to include clear instructions, safety guidelines, and explicit integration of green chemistry principles such as waste minimization and the use of safer reagents. This approach aligns with other studies that developed practical guides incorporating sustainability criteria, demonstrating that intentional design can support not only content clarity but also environmental responsibility in lab work (Amdayani, 2021).

During the Develop phase, validation by media and subject matter experts affirmed the guide's high standards of content and presentation. These expert reviews ensured that the guide was educationally sound and suitable for implementation. Supporting research also reports very valid and practical outcomes when green chemistry practicum materials are vetted by multiple validators, confirming the importance of expert assessment in producing high–quality instructional materials. The high practicality scores from both teachers and students suggest that the guide is not only theoretically valid but also user–friendly and functional in real classroom laboratory settings. Students indicated that the structured format and the environmental context helped them better understand the tasks and the purpose of each activity. This is coherent with findings from other R&D studies that link green chemistry guides to increased student motivation and usability in practicum contexts (Setianingsih, 2023)

Effectiveness, as measured by the improvement in pretest and posttest scores (N-Gain values), supports the claim that the guide enhances student learning outcomes, The effectiveness of the product showed a result of 68%, categorized as "Fairly effective.". This effect is consistent with literature showing that green chemistry practicum approaches can lead to better conceptual understanding in topics such as reaction rates when compared to conventional methods. Moreover, observations of student behavior during practicum indicate improved scientific attitudes such as responsibility, cooperation, and environmental awareness (I Wayan Redhana & Luh Maharani Mert, 2022). Research in chemistry education suggests that when laboratory activities explicitly incorporate sustainability and safety considerations, students develop stronger environmental literacy and process skills in addition to cognitive gains (Izza Kamilah & Isana Supiah Yosephine Louise, 2025).

Although the Disseminate stage was limited in this study, the guide's introduction to teachers and its positive reception imply strong potential for wider adoption. Expanding dissemination and perhaps digitizing the guide (e.g., e-module or online format) could further enhance accessibility and sustainable practices across schools. Similar interventions in other contexts show positive student responses when green chemistry materials are made available in user-friendly formats (Sura Menda Ginting dkk., 2023)

CONCLUSION AND RECOMMENDATIONS

Based on the results of this study, it can be concluded that the green chemistry-based chemistry practicum guide developed using the 4D model is valid, practical, and effective for supporting chemistry learning at senior high school Muarasipongi. The validation results from subject matter and media experts indicate that the product meets content accuracy, presentation, and language feasibility criteria. Teacher and student responses show that the practicum guide is easy to use and applicable in laboratory activities, while the improvement in students' learning outcomes and scientific attitudes demonstrates its effectiveness. Therefore, the developed practicum guide can be used as an alternative learning resource to promote safe, meaningful, and environmentally friendly chemistry practicum activities. Future research is recommended to involve a broader sample and longer implementation period to examine the long-term effectiveness of green chemistry–based practicum guides in improving students' learning outcomes, scientific attitudes, and environmental awareness across diverse school contexts.

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