Indonesian Society for Science Educators

Journal of Science Learning

journal homepage: ejournal.upi.edu/index.php/jslearning

Innovation of Acid-Base Learning with Green Chemistry Approach using Problem-Based Learning to Improve Students' Critical Thinking Skills

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ABSTRACT The Purpose of this research is to produce an acid-base learning device with a green chemistry approach, with a problem-based learning approach that improves the students' critical thinking skills according to the validity, practicality, and effectiveness of the learning device. This is R&D developing research using the 4D style process. The main results demonstrated the tool's feasibility. The learning device was deemed valid, with a mode score of 4, based on content and construction criteria. The practicality of learning devices in terms of learning implementation, learner activities, and learner responses was outstanding in both limited and broad trials, thus supporting their practicality. The effectiveness of the learning devices was assessed by significant differences between pretest and posttest scores using the Wilcoxon test and by improvements in critical thinking skills, as indicated by N-gain scores ranging from 0.35 to 1.00 in the moderate and high categories. Based on the results of validity, practicality, and effectiveness of learning devices, learning devices are obtained that are feasible to use.

Keywords: Learning devices, Problem-based learning, Green chemistry, Critical thinking skills

1. INTRODUCTION

Chemistry education combines theoretical concepts with practical applications, enabling students to understand scientific interactions and apply these in real-world contexts (Kemendikbudristek Number 32 of 2024; Anisah et al., 2025). This research focuses on acid-base materials due to their everyday relevance and inherent complexity, including understanding pH relationships and performing chemical calculations. Notably, these lessons provide students with opportunities to practice scientific methods. Given these demands and learning goals, a practical laboratory practicum is essential for developing critical thinking in acid-base topics.

Practicum activities clarify chemistry concepts and foster critical thinking by developing interpretation, analysis, and evaluation skills (Anisah & Nasrudin, 2023; Al-Hafidz et al., 2024; Astalini et al., 2022). Critical thinking, defined as the ability to analyze, assess, and reason objectively (Hartati et al., 2022), is best developed through hands-on laboratory experiences. However, preliminary research by Anisah et al. (2025) shows that practicum is rarely implemented, mainly due to limited facilities, which restrict students to theoretical or video-based labs. Teacher interviews confirm this limitation, highlighting missed opportunities for nurturing critical thinking. As defined by Facione (2015), critical thinkers demonstrate interpretation, analysis, evaluation, inference, explanation, and self-regulation—all of which require exposure to practical activities.

Globally, education is increasingly demanding that students possess scientific literacy, environmental awareness, and strong critical thinking skills. Chemistry education contributes to achieving the Sustainable Development Goals (SDGs), specifically Quality Education (Goal 4) and Responsible Consumption and Production (Goal 12). However, conventional chemistry practices may undermine these goals if they neglect safety, environmental impact, and sustainability. This highlights the pressing need to integrate green chemistry and critical thinking as fundamental aspects of chemistry education.

Developing critical thinking aligns with the Independent Curriculum, which prioritizes values outlined in the Pancasila Learner Profiles—among them critical and creative thought (Kemendikbudristek, 2022). This approach also introduces 21st-century skills, focusing on preparing lifelong learners adaptable to change and

Received: 20 May 2025
Revised: 28 July 2025
Published: 30 September 2025

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complexity. Partnership for 21st Century Skills (P21) identifies critical, creative thinking, communication, and collaboration as essential competencies (Ananda et al., 2021).

Critical thinking skills remain low among students, as evidenced by research conducted at MA Burhanul Hidayah Krembung and Al-Azhar Menganti: only around one-third of students reached acceptable levels in key critical thinking indicators. These deficits underscore the need for targeted improvements in the development of critical thinking within chemistry education.

Further supporting this, results from PISA 2022 and TIMSS 2015 indicate that Indonesian students struggle with higher-order thinking as assessed through international benchmarks, due in part to traditional, teacher-centered learning models that fail to support active critical thinking development (OECD, 2023; Mullis et al., 2015, 2020; Sudirman et al., 2023; Widyapuraya et al., 2023).

Preparing students for the demands of the 21st century requires emphasizing critical thinking, particularly through practicum activities that apply the scientific method (Yusri et al., 2023; Anisah et al., 2025). However, conventional laboratory practicums often use hazardous chemicals, posing environmental risks. To support sustainable development, a green chemistry approach is needed, which merges environmental responsibility with opportunities to build critical thinking, making laboratory work both safe and intellectually challenging (Inayah et al., 2022; Purwanti et al., 2023; Ayirahma & Muchlis, 2023; Al-Idrus et al., 2020; Qulub et al., 2023).

According to Anastas and Warner (1998), there are 12 principles of green chemistry, which aim to reduce environmental and human health impacts. This study focuses on principles 1, 5, and 12 because these three principles are relevant to the safety and sustainability of practicum in the laboratory, especially acid-base materials. Principle 1 emphasizes avoiding the formation of toxic waste and the importance of managing the remains of acid and base solutions. Principle 5 relates to the use of safe solvents and supporting materials to ensure that the chemicals used do not pose a risk to the environment or learners' safety. Principle 12 ensures the selection of safer chemicals to prevent accidents and the consistent use of safety equipment in the laboratory. Therefore, an effective learning model is necessary to enhance students' critical thinking and problem-solving skills in everyday life applications of green chemistry (Pohan & Rambe, 2022). This is supported by Tyas et al. (2020), who state that critical thinking skills can be improved through learning using the Problem-Based Learning. In line with research by Chairatunnisa et al. (2023), selecting the right learning model and devices that meet learners' needs can encourage the development of critical thinking skills, aligning with the curriculum objectives and the demands of the 21st century.

Problem-based Learning is a model of learning that centers on students, involving them in solving problems from around the world, encouraging active learning through a scientific approach and group discussions (Manasikana et al., 2022). Implementing Problem-Based Learning could enhance students' critical thinking skills by using problems relevant to everyday life, as supported by Ayirahma and Muchlis' (2023) research. This research demonstrated that a worksheet-based Problem-Based Learning approach can significantly enhance students' cognitive learning and critical thinking skills in the context of acid-base material from a green chemistry perspective. Research by Saputri and Suprihatiningrum (2023) also revealed that applying green chemistry through Problem-Based Learning can significantly enhance critical thinking skills and encourage students to take a greater interest in the environment. Previous research has focused more on the development of worksheets, whereas a more comprehensive approach is needed for learning, including teaching modules, learning media, and teaching materials.

The novelty of this study lies in the development of a comprehensive set of acid-base learning devices, teaching modules, student worksheets, and e-modules that integrate green chemistry principles and problem-based learning, simultaneously training students' critical thinking skills and environmental awareness. This comprehensive innovation not only addresses gaps in previous research that focused on individual components but also aligns directly with global efforts to create sustainable, environmentally responsible science education.

Based on this background, researchers developed an acid-base teaching innovation that incorporates green chemistry principles and uses problem-based learning to enhance students' critical thinking skills. To support acid-base learning innovation, learning devices are needed that are feasible to use and valid, practical, and effective. The learning devices needed are teaching modules, worksheets, and E-Modules (Anisah et al., 2025). Teaching modules contain guidelines and structured learning experiences (Salsabilla et al., 2023); worksheets are a teaching material that contains a series of activities that students must do in learning (Hamidah et al., 2018); and E-Modules are learning media in the form of reading materials, questions that are packaged electronically (Hasan et al., 2021).

2. METHOD

This research was a Research and Development (R&D) study (Mesra et al., 2023) that used a 4D development model (define, design, develop, disseminate) (Ibrahim, 2014) as seen in Figure 1.

The stages of learning device development are based on the 4D model (Define, Design, Develop, Disseminate). In the definition stage, an assessment is conducted of the objectives related to the learning material for which the device will be developed. The Define stage includes

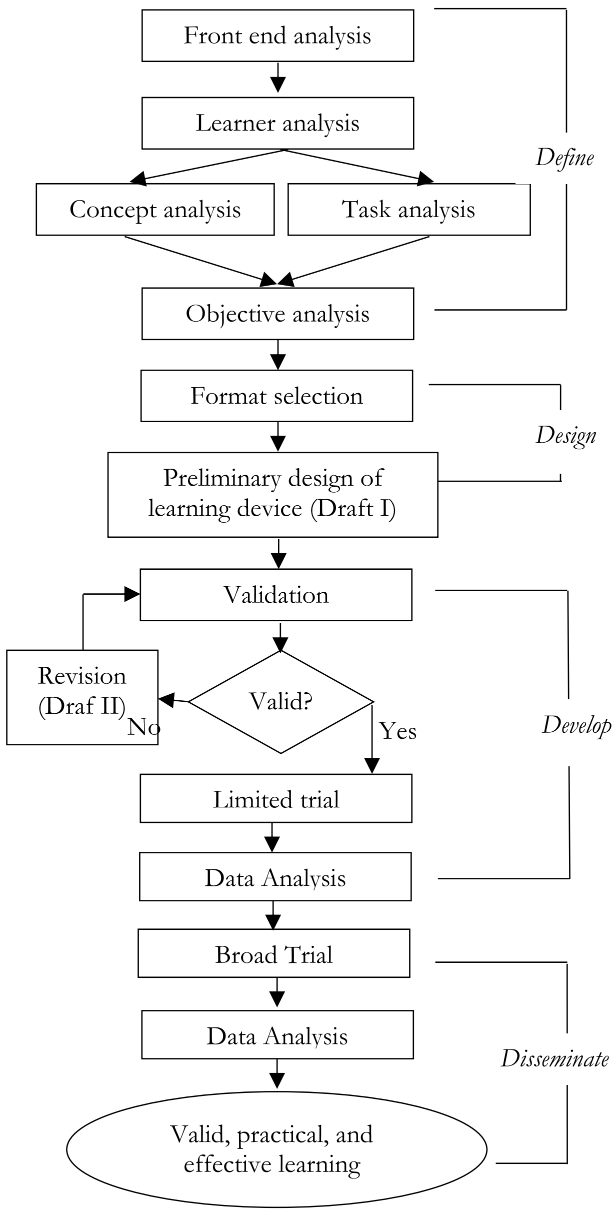


Figure 1 4D development design (Ibrahim, 2014)

preliminary analysis, learner analysis, concept analysis, and task analysis. In the planning stage, learning device design activities are conducted, including format selection and initial device design. The Design stage includes determining learning objectives, selecting a format, and preparing an initial draft of the device (Draft I), which is then validated. If it is not yet valid, a revision is made (draft II). The development stage involves designing and testing the device. The Develop stage includes limited testing and data analysis, followed by extensive testing and further analysis in the Disseminate stage. The result is a valid, practical, and effective learning device for use in the teaching and learning process.

The target of this research is the feasibility of learning devices in terms of validity, practicality, and effectiveness (Nieveen, 2010). The learning devices were limitedly tested in class XI in one class on January 2-4, 2025, and underwent a broader trial in two classes on February 6-9, 2025, at MA Burhanul Hidayah, Krembung, Sidoarjo. The design used in the limited trial and extensive trial was a one-group pretest-posttest design. The research activity began with a pretest to assess the students' initial abilities. Next, the learning device was used as a treatment during the learning process. The study concluded with a posttest to assess students' critical thinking skills following the treatment.

This study used research instruments comprising learning device validity sheets, learning implementation observation sheets, student activity observation sheets, student response questionnaires, and critical thinking skills tests. Feasibility in the validity aspect is reviewed based on content and construct criteria. Three lecturers from Surabaya State University assessed the device's validity. The validity data were analyzed both descriptively and quantitatively, with percentages calculated from the Likert scale, as shown in Table 1.

The data obtained is then searched for the mode score, and subsequently interpreted in Table 2.

The acid-base learning device is considered valid if it achieves a mode greater than 3 (Sari & Agustini, 2024).

Feasibility in the practicality aspect is based on the implementation of learning, students' activities, and students' responses. The learning implementation is assessed by the extent to which the teacher can follow the problem-based learning syntax designed in the learning device, as observed by three observers, using the assessment criteria in Table 3.

Table 1 Likert scale

Score	Description
5	Very good
4	Good
3	Fair
2	Less
1	Very Less

Table 2 Interpretation of mode score

Mode Score	Category
1	Not valid
2	Less valid
3	Quite valid
4	Valid
5	Very valid

Table 3 Implementation assessment score

Score	Description
1	Not good if the learning activity is not implemented.
2	Less good if the teacher's delivery is less clear.
3	Good, if the teacher's delivery is quite clear.
4	Very good, if the teacher's delivery is obvious.

The results of the assessment are calculated using the formula:

$$\text{Implementation score} = \frac{\text{Score obtained}}{\text{Maximum score}} \times 100$$

The obtained implementation score was then interpreted according to the criteria outlined in Table 4.

Learning implementation is considered adequate if it achieves a percentage of≥ 61%.

The learner activity aims to assess the extent of learner involvement in the learning process using the developed device. Learner activity data is collected through observations, which are calculated based on the average of 3 observers using the formula:

$$\text{Percentage (\%)} = \frac{\text{Activity that appears}}{\text{Overall activity}} \times 100\%$$

The percentage results are then interpreted as scores in Table 5.

Students' activities are considered reasonable and support learning if the percentage of relevant activities is 61% or higher.

Learners' responses were taken after participating in the learning process using the developed tools. The assessment of the learner response questionnaire is calculated using the Guttman scale, as shown in Table 6.

The data obtained can be used to calculate the percentage using the formula:

$$\text{Percentage} = \frac{\text{Number of respondents' answers}}{\text{Number of respondents}} \times 100\%$$

The results obtained are interpreted in accordance with the criteria presented in Table 7.

A positive student response to the learning device is considered good if the percentage is ≥ 61%.

Feasibility in the effectiveness aspect is reviewed based on the results of the critical thinking skills test, including the increase in scores from pretest to posttest. The score of students' critical thinking skills can be calculated using the formula:

$$\text{Score} = \frac{\text{Score obtained}}{\text{Maximum score}} \times 100\%$$

The data were tested for normality using the Shapiro-Wilk test because the sample size was <50. If the data were normally distributed, the paired-samples t-test was used; otherwise, the Wilcoxon signed-rank test was used to analyze significant differences between the pretest and posttest. The data was then analyzed using N-gain to analyze the improvement of critical thinking skills with the formula:

$$< g > = \frac{(\text{Posttest score} - \text{Pretest score})}{(\text{Maximum score} - \text{pretest score})}$$

The N-gain value is then interpreted in the N-gain score criteria in Table 8.

Critical thinking skills are said to increase if the N-gain value is≥ 0.7 with high criteria or 0.3 ≤ <g> < 0.7 with moderate criteria, indicating that the learning device is efficacious in improving critical thinking skills.

Table 4 Interpretation of the implementation score

No	Percentage	Category
1	0% – 20%	Very less
2	21% – 40%	Less
3	41% – 60%	Fair
4	61% – 80%	Good
5	81% – 100%	Very good

Table 5 Interpretation of learner activity scores

No	Percentage	Category
1	0% – 20%	Very less
2	21% – 40%	Less
3	41% – 60%	Fair
4	61% – 80%	Good
5	81% – 100%	Very good

Table 6 Guttman scale

Answer	Value/Score
Yes	1
No	0

Table 7 Interpretation of learner response scores

No	Percentage	Category
1	0% – 20%	Very less
2	21% – 40%	Less
3	41% – 60%	Fair
4	61% – 80%	Good
5	81% – 100%	Very good

Adaptation (Riduwan, 2015)

Table 8 N-gain score criteria

Interval	Criteria
$<g> \geq 0.7$	High
$0.3 \leq <g> < 0.7$	Medium
$g < 0.3$	Low

3. RESULT AND DISCUSSION

This study aims to assess the feasibility of acid-base learning devices that incorporate a green chemistry approach, using a problem-based learning model to enhance students' critical thinking skills. The feasibility of learning devices is reviewed in terms of validity, practicality, and effectiveness. The results and discussion are based on the 4D model's stages.

3.1 Define

The define stage aims to examine and determine the material and its limitations, analyze the needs of the learning devices to be developed, and the form of presentation of these learning devices (Zamsiswaya et al., 2024). There are five main steps in the definition stage, namely initial needs analysis, student characteristics analysis, task analysis, concept analysis, and formulation of learning objectives (Supardi, 2022).

Front End Analysis

The front-end analysis aims to identify the primary issues in chemistry learning, particularly in the context of acid-base material. Based on preliminary observations and literature reviews, several problems were identified that hindered learning effectiveness, including a lack of student involvement in the learning process, limited environmentally friendly practicum facilities, and suboptimal application of scientific approaches to develop critical thinking skills. The analysis was conducted through a curriculum review, literature study, and examination of student needs for contextual learning relevant to the Pancasila Student Profile in the Independent Curriculum. To address these issues, a Problem-Based Learning device was developed, integrated with a green chemistry approach, to create contextual, environmentally friendly acid-base learning and to foster 21st-century skills.

Learner Analysis

Student analysis was conducted to adjust learning devices to students' cognitive characteristics. Eleventh-grade students were selected because they are at the formal operational stage of cognitive development according to Piaget's theory (Ariani et al., 2022). At this stage, students can think abstractly and logically, and understand complex concepts, such as those in acid-base material. The concept of acids and bases in chemistry involves three levels of representation: macroscopic, which refers to directly observable phenomena such as changes in indicator color or reactions between acids and bases; microscopic, which involves understanding particles such as $H^+$and OH^- ions in solutions; and symbolic, which involves the use of chemical formulas, reaction equations, and pH calculations (Anisah & Nasrudin, 2023). These three levels are interrelated and necessary for a comprehensive understanding of the topic. Grade XI students have the cognitive readiness to relate these three levels. Therefore, acid-base learning will be more effective if presented interactively, such as through practicums, which can help connect macroscopic phenomena with microscopic and symbolic explanations, while training students' critical and analytical thinking skills.

Task Analysis

Task analysis aims to identify the tasks students must perform to learn about acids and bases using a green chemistry approach and problem-based learning. The learning process is designed in three sessions, with time allocated based on the curriculum, the complexity of the acid-base material, which covers three levels of chemical representation (macroscopic, microscopic, and symbolic), and sufficient time for in-depth experiments and discussions. Each meeting has a focus on continuous activities: In the first meeting, a practicum is conducted with the title of making natural acid-base indicators, in the second meeting, a practicum is conducted with the title of determining the strength of acids and bases, and in the third meeting, a practicum is conducted with the title of determining the concentration of solutions through acid-base titration.

The series of learning activities is designed according to the principles of Problem-Based Learning and scientific principles to develop students' critical thinking skills and environmental awareness. The following sequence of activities is designed systematically:

- Observe and argue the phenomenon of motivation.
- Observe the phenomenon of problem-based learning.
- Formulate problems based on the concept of problem-based learning.
- Make hypotheses from various sources.
- Designing experiments based on problem-based learning phenomena.
- Collecting data and applying green chemistry principles, namely principle 2, principle 5, and principle 12.
- Analyze the data from the experiment.
- Making conclusions.
- Presenting the results.
- Evaluate the answer.

With this design, it is hoped that students will not only thoroughly understand the concept of acids and bases but also develop environmental awareness and critical thinking skills.

Concept Analysis

Concept analysis systematically determines and organizes the main concepts into concept maps, thereby supporting the development of structured learning devices (Figure 2).

Acids and bases play an important role in daily life and industry. The acid-base material in the learning tool to be developed discusses how acids and bases interact in

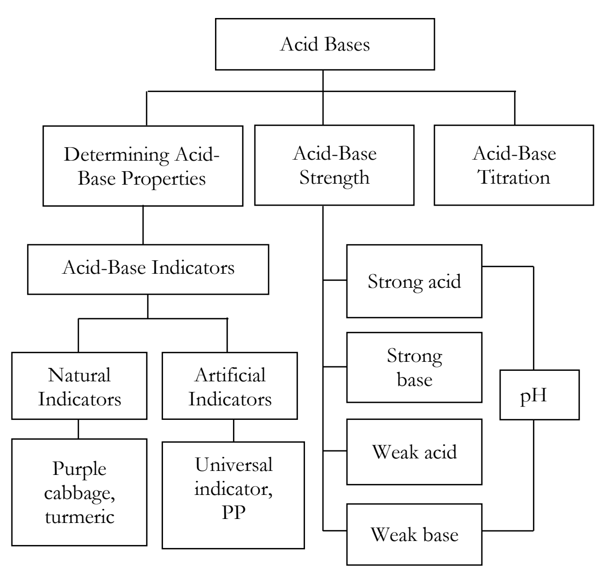


Figure 2 Concept map of acid-base subject matter

everyday life, the indicators used to detect the nature of acids and bases, the strength of acids and bases, and the concept of titration. A green chemistry approach will be applied to minimize environmental impacts and improve the sustainability of chemical processes. Acids and bases play a crucial role in everyday life, from food ingredients to cleaning products. In addition, learners will be introduced to acid-base indicators, such as litmus paper and natural indicators, which help determine whether a solution is acidic or basic. The strengths of acids and bases will then be explained in terms of their degree of dissociation. If the value of $\alpha = 1$, then the acid-base is strong or perfectly ionized, and if the value of the degree of ionization is $1>\alpha>0$, then the acid-base is weak or partially ionized. As well as the introduction of acid-base titration as a method to calculate the exact concentration of an acid or base solution.

Learning Objectives Analysis

Based on concept and task analysis, learning objectives are systematically organized in the Flow of Learning Objectives to ensure the achievement of expected competencies through the green chemistry approach and problem-based learning model.

3.2 Design

The learning device design stage aims to develop the design of teaching modules, worksheets, and E-Modules. This stage consists of two main steps: determining the format and designing the initial layout (Supardi, 2022).

Format Selection

The selection of learning device formats was based on the objectives of increasing student engagement, facilitating the understanding of complex concepts, and encouraging critical thinking skills and environmental awareness. Therefore, the learning devices were designed as teaching modules, student worksheets, and interactive e-modules. The teaching module and worksheet formats are adapted to the problem-based learning and green chemistry approach, as both have proven effective in stimulating critical thinking skills through exploratory activities and real-world problem-solving. Elements such as motivational phenomena, problem-based learning phenomena, and indicators of critical thinking skills are incorporated to build connections between learning experiences and daily life, and to encourage reflection and scientific reasoning among students. The green chemistry box in the worksheets reinforces the understanding of sustainability values in chemistry practice.

The e-module format was chosen as an interactive flipbook to make it more visually appealing and accessible to students, especially in the context of increasingly advanced digital learning. The e-module design includes text, images, practicum videos, and exercises arranged in a sequence to support independent learning. The structure of activities in the e-module also follows the problem-based learning stages across three meetings, with each meeting designed to integrate practicums (making natural indicators, measuring acid-base strength, and titration) as concrete media to bridge macroscopic, microscopic, and symbolic concepts. With this format, the learning device is expected to create an active, contextual, and meaningful learning experience, while also supporting the achievement of the Pancasila Student Profile.

Initial Design of Learning Devices

At the initial design stage, researchers began developing learning devices from teaching modules, worksheets, and E-Modules, resulting in an initial design or draft I with guidance from the supervisor.

3.3 Develop

The development stage aims to produce ready-to-use products through validation by three validators. After being declared valid, the product was tested on a limited basis. The steps in the development are: (1) validation of learning devices on validators; (2) revision based on input from validators to produce draft II; (3) limited trials through classroom learning; (4) data analysis (Supardi, 2022).

Validity of Learning Devices

The validity of learning devices is established through validity results obtained from three lecturers at Surabaya State University, based on content and construct criteria. Data on the validity of learning devices are presented in Figure 3.

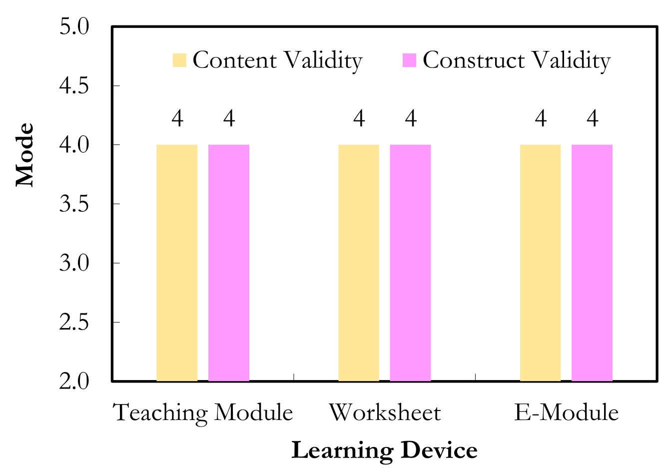


Figure 3 Learning device validity mode

A teaching module is a systematic teaching and learning program unit to help students achieve learning objectives (Salsabilla et al., 2023). The teaching module was developed into three subchapters: acid-base indicators, acid-base strength, and acid-base titration. It used the problem-based learning model, combined with a green chemistry approach, to enhance critical thinking skills. The content validity of the teaching module was assessed based on the suitability of the learning outcomes and the applicable curriculum(Astuti et al., 2024).

Based on Figure 3, the mode score for both content validity and construct validity across all learning devices, teaching modules, worksheets, and e-modules is 4. This indicates that the experts consistently assigned the highest frequency rating of 4 (very valid) to all assessed aspects, supporting the conclusion that the learning devices are highly valid across both content and construct dimensions. Such consistent ratings indicate that the materials are not only aligned with curriculum demands and learning objectives but are also presented in a comprehensive, systematic, and engaging manner, thereby fulfilling the expectations for practical instructional tools.

The teaching module is divided into three sections: General Information, Core Information, and Appendix. General information in the teaching module is in accordance with the Ministry of Education and Culture guidelines, including the author's identity, pancasila student profile, facilities and infrastructure, target students, and the learning model used (Anggraena et al., 2022). The identity of the teaching module consists of the author's name, institution, year of creation, school level, class/phase, subject, subject matter, learning mode, learning model, time allocation, and keywords (Koesnadi & Astuti, 2024). The profile of Pancasila students in the teaching module aligns with the objectives of national education by instilling character and competence rooted in Pancasila values (Purnawanto, 2022). Every teacher needs facilities and infrastructure to support learning (Koesnadi & Astuti, 2024). Device development is tailored to students' needs (Anisah & Nasrudin, 2023).

According to the Ministry of Education and Culture's guidelines, the core information comprises objectives, meaningful understanding, triggering questions, learning activities, and assessments (Anggraena et al., 2022). Learning objectives are made based on the analysis of learning outcomes and the flow of learning objectives (Heryahya et al., 2022). Meaningful understanding in the teaching module encompasses concepts, information, and learning activities designed to help learners connect new knowledge with existing knowledge, enabling it to be applied in various real-life contexts. Triggering questions are questions that foster curiosity and review the material of the previous meeting. Learning activities in the teaching module are structured according to the principles of problem-based learning, a learner-centered approach that utilizes real-world problems to develop critical thinking skills. The assessment in the teaching module consists of affective, cognitive, and psychomotor assessments (Maulida, 2022).

The appendix in the teaching module comprises worksheets, enrichment and remedial materials, reading materials, a glossary, and a bibliography (Anggraena et al., 2022). Enrichment and remedial support are provided to high-achieving learners and to those who require guidance in understanding the material (Maulida, 2022). Teacher and learner reflection evaluate the effectiveness of learning to improve its quality. The teaching module glossary contains important terms and their explanations to facilitate understanding of concepts. The attachment of learning materials and media to the teaching module is the learner worksheet and the E-Module.

Worksheets are one of the teaching materials and learning resources that can support the learning process, used to minimize educators' roles and further activate students' roles (Anisah & Nasrudin, 2023). A worksheet developed for as many as three sessions on acid-base learning, covering acid-base indicator material, acid-base strength, and titration. The material presented in the worksheet contains facts, concepts, and images that align with the lesson's content, ensuring the information provided is accurate, relevant, and supports students' understanding (Anisah & Nasrudin, 2023). Problem based learning phenomena must be factual and relevant to everyday life (Sofyan et al., 2017), with the phenomena used in meeting one entitled "Turmeric and tamarind herbal medicine from Sidoarjo", meeting two entitled "The difference in effectiveness of acid cleaners: why is HCl more effective than vinegar in removing scale?" and meeting three entitled "Acid-base titration: how to identify drinks that are safe for people with ulcers". Learning becomes more focused by adjusting to the syntax of the learning model, specifically problem-based learning (Anisah & Nasrudin, 2023). The suitability of green chemistry worksheets for learning is important because they help students understand the impact of chemistry on the environment, encourage process efficiency and waste reduction, and increase awareness of the management of residual practicum materials (Azzajjad et al., 2024). The suitability of the worksheet in terms of indicators of critical thinking skills is crucial for supporting the independent curriculum and the skills required in the 21st century (Susanti et al., 2020). The critical thinking skills indicators used include interpretation, analysis, inference, evaluation, and explanation (Facione, 2015).

E-modules, assisted by flipbooks, are electronic learning media that contain readings to facilitate independent learning, featuring interactive displays, flexible access, and efficient material distribution. E-Modules contain module identity, learning outcomes, a brief description of the material, module instructions, objectives, phenomena, material descriptions, exercise questions and discussions, questions to test students' understanding, material summaries, and competency test questions. E-Module instructions guide teachers and students in using the module (Syahiddah et al., 2021). E-Modules must present factual phenomena relevant to students' environments and in accordance with the material being taught, while facilitating the achievement of learning objectives through a complete, systematic, clear, concise, and easy-to-understand description of the material. In addition, as an independent learning medium, E-Modules are equipped with practice questions, discussions, and competency tests designed to help students learn independently, deepen understanding, and effectively measure achievement of competencies and critical thinking skills (Takim, 2021). E-Modules are designed with practicum activities based on problem-based learning, which encourages students to identify problems, design experiments, and find solutions independently (Hidayati & Khoiroh, 2024).

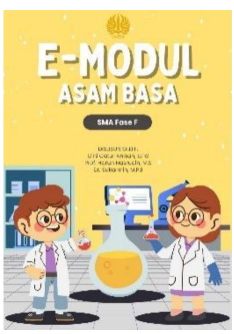
On the construct validity of learning devices, including teaching modules, worksheets, and E-Modules, it focuses on the information presented being complete, the cover being attractive and relevant, the selection of font type and size can facilitate readers, the harmony of text layout, and using good and correct Indonesian language (Anisah & Nasrudin, 2023). Regarding the construct validity of learning devices, including teaching modules, worksheets, and E-Modules, the consistent mode score of 4 (as shown in Figure 3) indicates that the layout, design, language use, and information presentation meet high-quality standards. This supports the appropriateness of these learning tools for classroom use and their potential to enhance the learning process effectively.

Revision Based on Validator Feedback

Based on the feedback, improvements were needed in the writing style, content structure, alignment with the Profil Pelajar Pancasila, and the logical flow of learning components. In the teaching module, validators emphasized that the Pancasila Student Profile section should be more elaborated to reflect better the values and competencies expected; they also noted that the sequence of learning outcomes needed to be arranged more systematically. For the learning model implementation, particularly Problem-Based Learning, validators advised that the phenomenon used as a stimulus should be introduced precisely during the problem orientation stage, not earlier, to align with the correct syntax of problem-based learning. In the worksheet, suggestions focused on refining the writing style to match students' reading levels and enhancing instruction clarity. For the e-module, validators recommended adjustments to the formulation of learning objectives to align them with the analysis of learning outcomes, the learning flow, and expected competencies.

To enhance clarity and accessibility of the feedback, the suggestions have been summarized in Table 9.

Figure 4 and Figure 5 illustrate the improved structure and features of the e-module and worksheet following these revisions.



E-Module Cover


Module identity, CP, Material summary

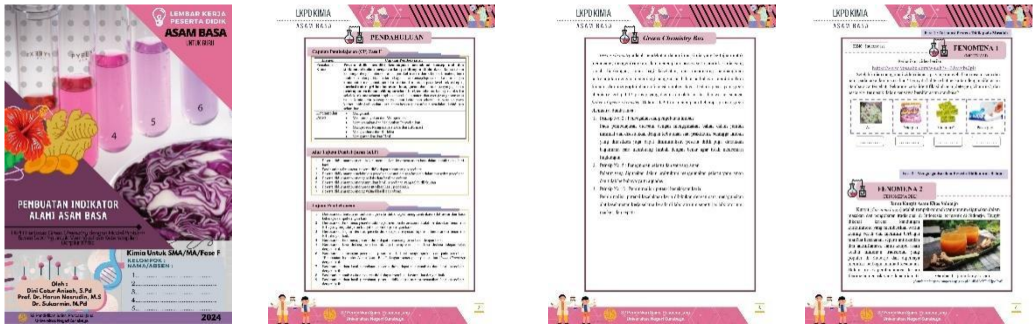

Module instructions, material content, Pancasila student profile


Learning activities are equipped with pictures and videos made in 3 activities


The content of the module contains material, questions, discussions, summaries, and practice questions

Green chemistry

Figure 4 E-module features



Worksheet Cover | Learning Outcome | Green chemistry box | Motivational phenomena, and problem based learning and the scientific method

Figure 5 Worksheet features

Table 9 Summary of validator suggestions on learning devices

Component	Suggestions for Improvement
Teaching Module	Improve writing clarity and flow Elaborate more on the Pancasila Student Profile Arrange learning outcomes more systematically
Worksheet	Adjust the placement of phenomena in the problem-based learning stage Refine writing style to suit the student's level Ensure clarity and accuracy in instructions
E-Module	Align learning objectives with learning outcomes and competency analysis Strengthen content structure and consistency of features

Limited Trial

In a limited trial, researchers used learning devices with students in 1 research class, employing a one-group pretest-posttest design. Practicality data includes learning implementation, learner activities, and learner responses. The results of the learning implementation trial are presented in Table 10.

Learning using the developed device demonstrated excellent implementation, with percentages of meetings 1, 2, and 3 being 88.89%, 88.83%, and 90.00%, respectively, which supports the practicality of the learning device. In line with Dewi et al. (2024), teachers' implementation of problem-based learning reached an average of 83.33% (in the good category), indicating their ability to manage learning, convey objectives, guide discussions and worksheets, and create an engaging learning environment through learning media. The main features of Problem-Based Learning include: learning begins with a problem to activate students' interest in learning; it is student-centered; it is implemented through small-group collaboration; the teacher acts as a facilitator; and it encourages independent learning (Wijnia et al., 2024).

The results of the students' activities in the limited trial are presented in Table 11.

Student activity during learning yielded excellent results, with relevant activities consistently outperforming irrelevant ones across all sessions. The percentages of relevant activities in meetings 1, 2, and 3 were 91.94%, 89.01%, and 93.90%, respectively, while the percentages of irrelevant activities were 8.06%, 10.99%, and 6.10%. This supports the practicality of the learning device. This finding is relevant to Anisah and Nasrudin's (2023) research, which revealed that 95.02% and 96.56% of activities were deemed relevant, indicating that teaching activities ef
fectively support the learning process.

Table 10 Data on the applicability of the limited trial

Meeting	Percentage (%)	Category
1	88.89	Very good
2	88.33	Very good
3	90.00	Very good

Table 11 Limited trial learner activity data

Meeting	Activity Percentage (%)	
	Relevant	Not Relevant
1	91.94	8.06
2	89.01	10.99
3	93.90	6.10

Table 12 Limited Trial Learner Response Data

Percentage of Positive Response(%)	Category
93.05	Very good

The results of the students' responses in the limited trial are presented in Table 12.

Based on the results of the questionnaire on students' responses to learning devices in limited trials, positive responses were obtained with an average percentage of 93.05 in the outstanding category, which is relevant to other research results stating that if students' responses are positive and support the practicality of the device, they will receive a percentage of 98% in the convenient category (Anisah & Nasrudin, 2023).

The effectiveness data, in the form of pretest and posttest scores, were tested for normality using the Shapiro-Wilk normality test. The results of the normality test for the limited trial are shown in Table 13.

Based on the normality test, the significance value in the limited trial was <0.05, indicating that the pretest and posttest data were not normally distributed. The data were then tested using the Wilcoxon Test. The results of the Wilcoxon test on the limited trial are in Table 14.

Effectiveness data from pretest and posttest comparisons were analyzed with N-gain. The N-gain value of the limited trial ranged from 0.35 to 0.90 in the medium and high categories. The improvement of each component of critical thinking skills is presented in Table 15.

The N-gain data on critical thinking skills showed an increase from 0.64 to 0.83 in the moderate-to-high category. This indicates that the learning device is efficacious in improving students' critical thinking skills. In limited trials, the interpretation indicator in critical thinking skills received a lower N-gain score because students still had difficulty formulating problems from the given phenomena. Further research is expected to improve this ability.

The learning device is declared feasible based on: (1) Validity, with a mode of content and construct criteria of 4 each in the valid category in teaching modules, worksheet, and E-Modules; (2) Practicality, as evidenced by the implementation of learning, activities, and student responses; and (3) Effectiveness, with pretest and posttest data significantly different based on the Wilcoxon test and N-gain values of 0.64-0.83 in the medium-high category, shows an increase in critical thinking skills. Based on the feasibility of the learning devices developed, they are promising at the limited trial stage, so the research is continued to the next stage, namely the dissemination stage.

3.4 Disseminate

Learning devices that have been refined through limited trials are then tested on a larger scale. The main stages of dissemination are field trials and data analysis. The broad trial was conducted in 2 research classes, namely classes B and C. Data on the practicality of the broad trial include learning implementation, learner activities, and learner responses—data on the effectiveness of the device, based on increases in pretest and posttest critical thinking skills.

Learning Implementation Data

Learning is facilitated through learning devices—teaching modules, worksheets, and e-modules —that are applied using the problem-based learning model, ensuring that all stages align with its principles. Data on the results of learning implementation in the broad trial are in Tables 16 and 17.

Based on the implementation of learning in classes B and C, a high percentage was achieved, placing it in the outstanding category, indicating that the learning was well done and supported the device's practicality.

Table 13 Normality test of limited trial

Tests of Normality			
	Statistic	df	Sig
Pretest	.935	40	.024
Posttest	.911	40	.004

Table 14 Wilcoxon test in the limited trial

Test Statistics	
	Posttest - Pretest
Z	-5.512b
Asymp. Sig. (2-tailed)	.000
a. Wilcoxon Signed Ranks Test	
b. Based on negative ranks.	

Table 15 Data on N-gain results for each critical thinking skills indicator

Indicator	Pretest	Posttest	N-gain	Category
Interpretation	36.67	77.08	0.64	Medium
Analysis	31.67	82.92	0.75	High
Inference	31.11	82.08	0.74	High
Evaluation	19.17	85.83	0.82	High
Explanation	20.83	86.67	0.83	High

Table 16 Data on the implementation of the broad trial Class B

Meeting	Percentage (%)	Category
1	90.28	Very good
2	95.83	Very good
3	96.94	Very good

Table 17 Data on the implementation of the broad trial Class C

Meeting	Percentage (%)	Category
1	92.50	Very good
2	98.33	Very good
3	98.06	Very good

Learning implementation refers to the suitability of teacher activities within the problem-based learning syntax, as measured through observation sheets completed by three observers across three meetings. Phase 1 provides students with an orientation to the problem. The activity begins with a greeting, prayer, and attendance check, followed by a review of the material from the previous meeting in the form of questions. The teacher also presents the phenomenon of motivation related to acids and bases in everyday life, then divides the students into groups for discussion, and provides instructions to read about the problem-based learning phenomenon. This activity is part of the problem orientation. The problem-based learning problem will then be used as a stimulus for conducting experiments in the next stage. According to Arends (2012), in phase 1, the teacher discusses the learning objectives, explains the key logistical requirements, and motivates students to engage in problem-solving activities.

Phase 2 organizes learners to research. In this phase, learners are directed to design experiments based on problem-based learning phenomena. However, the experiment is not derived directly from a pre-given problem-based learning phenomenon, but rather designed by students themselves to address the problem they identified during the orientation phase. Before experimenting, students are asked to formulate the problem, formulate a hypothesis, identify the necessary materials, and outline the experimental design. The results of the experimental design will be presented for discussion with other groups, and at the end, the teacher will justify the results. This process ensures that students' investigation is rooted in their own inquiry, enhancing ownership of learning. As noted by Arends (2012), in Phase 2, the teacher helps students define and organize learning tasks related to the problem.

Phase 3 helps with independent and group investigations. At this stage, students begin to undertake a practicum by applying the green chemistry approach introduced by the teacher. The green chemistry principles applied focus on three main principles, namely: (1) principle 2 of waste prevention and treatment, carried out with a solution with the amount according to practical needs without wasting the solution, so that the waste produced is small, and it needs to be emphasized that it is forbidden to dispose of waste carelessly into drains, soil, or trash without going through the correct process; (2) principle 5 of using safe solvents and substances, namely using distilled water solvents; and (3) principle 12 of minimizing the potential for work accidents, students are asked to wear safety when in the laboratory. The teacher guides and observes the practicum process to ensure that it is carried out according to the experimental design. As noted by Arends (2012), in Phase 3, the teacher encourages learners to obtain information to carry out experiments, provide explanations, and find solutions.

Phase 4: Develop and present work. The teacher asks students to discuss the analysis questions in the worksheet, draw conclusions, and present their results to the class. As noted by Arends (2012), in Phase 4, the teacher assists students in planning and preparing reports, documentation, or models, and in conveying or presenting the results to others.

Phase 5: Analyze and evaluate the problem-solving process. After the presentation, learners evaluate the answers with other groups and discuss the correct conclusions with the teacher's guidance. The teacher provides feedback and clarifies learners' understanding if necessary. The lesson concludes with a reflection, information about the following topic, and closing greetings. As noted by Arends (2012), in Phase 5, the teacher helps students reflect on their investigations and the processes they use.

The learning implementation with the developed device received excellent ratings in both limited and extensive trials, thus supporting its practicality. In line with Dewi et al. (2024), the teacher's implementation of the problem-based model in teaching reached an average of 83.33% in the good category, indicating successful learning.

Learner Activity Data

Data on student activities were collected through observation sheets completed by three observers, each observing 1–3 groups every 3 minutes. Analysis was performed using quantitative descriptive methods based on the average observations. Activities were considered good and supportive of the device's practicality if the percentage of relevant activities was ≥ 61%. Data on students' results in the broad trial are in Tables 18 and 19.

Table 18 Learner activity data Class B

Meeting	Activity Percentage (%)	
	Relevant	Not Relevant
1	95.26	4.47
2	91.95	8.05
3	88.87	11.22

Table 19 Learner activity data Class C

Meeting	Activity Percentage (%)	
	Relevant	Not Relevant
1	91.39	8.61
2	91.05	8.95
3	91.49	8.51

Learners' activities during the broad trial in both classes B and C showed excellent results, with the percentage of relevant activities exceeding that of irrelevant activities, indicating that the data support the practicality of the device.

The results of each activity are as follows. (1) The activity of paying attention to the teacher's explanation decreases with the meeting, indicating an increase in the independence of students in problem-based learning. (2) The activity of reading and understanding the problem-based learning phenomenon gets a constant percentage, meaning that students read the problem-based learning phenomenon used as a guide for practicum. (3) The activity of expressing opinions shows a high percentage in almost all meetings, reflecting the active involvement of students in critical thinking, discussing, and solving problems according to the given phenomenon (Manasikana et al., 2022). (4) The activity of formulating problems gets a relatively small percentage, and students still have difficulty. The formulation of the problem is used as a practicum problem (Anisah & Nasrudin, 2023). (5) The activity of making hypotheses gets a relatively low percentage because students are used to formulating hypotheses, and this activity does not require a long discussion. (6) The activity of designing experiments is used to discuss tools, materials, and experimental procedures (Tyas et al., 2020). (7) Data collection activities include taking materials, conducting experiments, recording results, washing tools, and returning, so it takes a long time. According to Nisa &

Nasrudin (2022), conducting experiments is the dominant activity. (8) Activities to apply green chemistry principles in practicum, including waste prevention, use of safe materials, and minimization of accident risks, have been consistently carried out and show increased awareness of the environment. (9) The activity of analyzing data involves students in discussions to answer analysis questions based on practicum results, with a reasonably high percentage, relevant to Anisah & Nasrudin (2023), the activity of analyzing data requires a relatively long time to discuss. (10) The activity of making conclusions is relatively minor compared to other activities, because, based on the answers to the analysis questions, students can easily make conclusions. (11) The activity of presenting results gets a relatively high percentage, meaning that students are gradually becoming more skilled and confident in presentation activities. (12) The activity of evaluating answers is important to reflect on the thinking process, assess the accuracy of answers, and correct mistakes. (13) Irrelevant activities get a low percentage.

Based on learner activities, a higher percentage of relevant activities was observed in both the limited and broad trials of classes B and C. Therefore, it can be stated that learner activities are practical and support the practicality of learning devices, indicating that they are practical to use.

Learner Response Data

A response questionnaire was used to measure students' responses to the learning devices, which were analyzed descriptively and quantitatively. “Yes” answers were given a score of 1, and “No” answers were given a score of 0 according to the Guttman scale. A device was considered to have received a positive response if the percentage was 61% or higher. Data on learner responses in the broad trial are in Table 20.

Table 20 Learner response data for the broad trial

Class	Percentage of Positive Response (%)	Category
B	95.37	Very good
C	96.61	Very good

Based on students' responses to learning in classes B and C, which received 95.37% and 96.61%, respectively, in the outstanding category, thus supporting the device's practicality. Students' responses to the acid-base learning were excellent, supported by relevant, engaging, and easy-to-understand worksheets and E-Modules. The problem-based learning worksheet helps improve critical thinking skills, learning motivation, and environmental awareness, while the interactive E-Module supports independent learning. The presentation of contextual material and practical learning media encourages students to be more active and enthusiastic participants in their learning.

The results of students' responses to learning are as follows. Motivational phenomena are associated with acid-base balance in everyday life, making them relevant, attracting attention, and increasing students' learning motivation (Purwanti et al., 2021). Problem-based learning phenomena in the form of real-life factual acid-base phenomena, which are then used as references in practicum or research (Sofyan et al., 2017).

The worksheet has been proven to improve students' critical thinking skills, as indicated by results from both limited and broad trials, with results in the excellent range. It is also effective in instilling an attitude of environmental care by applying green chemistry principles. Presenting the worksheet in print makes it easier for students to record the results of discussions and investigations/practicums because it provides space to write directly without distractions from electronic devices and is more accessible in environments with limited technology. The worksheet is arranged according to the Problem-Based Learning model, enabling students to conduct investigations and practicums, from formulating problems to concluding. The presentation of phenomena and images in the worksheet can increase students' motivation and engagement in learning about acid-base chemistry because it is relevant to everyday life. Practical activities can encourage students to work together in groups, thereby strengthening social interaction and communication.

The acid-base E-Module effectively enhances students' understanding by presenting coherent material, contextual phenomena, and practice questions that hone critical thinking skills. E-Modules developed in electronic format can be accessed on various devices and feature interactive elements such as videos, animations, and simulations. The main advantage of E-Modules over printed teaching materials is the flexibility of access and the integration of multimedia technology, which motivates students and supports independent learning. Workbooks and E-Modules are prepared using easy-to-understand language, a comfortable font type and size, and a selection of background and simple writing colors, making it easier for students to understand the material.

Critical Thinking Skills Test Data

The effectiveness data, in the form of pretest and posttest scores, were tested for normality using the Shapiro-Wilk test, and the results of the normality test across the broad trial of Classes B and C are shown in Table 21.

Table 21 Normality test of broad trial

Tests of Normality						
	Class B			Class C		
	Statistic	df	Sig	Statistic	df	Sig
Pretest	.886	32	.003	.794	23	.000
Posttest	.871	32	.001	.858	23	.004

Based on the normality test, the p-values for the limited and extensive trials were <0.05, indicating that the pretest and posttest data were not normally distributed. The data were then tested using the Wilcoxon Test. The results of the Wilcoxon test on the broad test are shown in Table 22.

Table 22 Wilcoxon test on broad trial

Test Statisticsa	Class B Posttest - Pretest	Class C Posttest - Pretest
Z	-4.939b	-4.203b
Asymp. Sig. (2-tailed)	.000	.000

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

The Wilcoxon test showed a significant difference ($p < 0.05$), indicating a difference in the average level of critical thinking skills between the pretest and posttest. Then, the Wilcoxon test on a wide trial obtained significant values in classes B and C, 0.000 and 0.000, which means $p < 0.05$, indicating a significant difference in the average value of critical thinking skills between the pretest and posttest.

The increase in pretest and posttest was then analyzed using N-gain. The N-gain value in class B ranged from 0.62 to 1.00 in the high category. The increase in each component of critical thinking skills in class B is presented in Table 23.

The N-gain value in Class C ranged from 0.78 to 0.90 in the high category. The improvement of each component of critical thinking skills in class B is presented in Table 24.

Based on the N-gain data, each component of critical thinking skills, namely interpretation, analysis, inference, evaluation, and explanation, gets an N-gain value ≥ 0.7 in the high category, so that each component of students' critical thinking skills is said to increase, and learning devices are effective for improving critical thinking skills.

Interpretation is the ability of learners to express and understand the meaning of various experiences, situations, data, events, and performances. Sub-skills: categorize, decode meaning, clarify meaning (Facione, 2015). In the developed learning devices, interpretation skills are trained

Table 23 N-gain data of class B

Indicator	Pre-test	Post-test	N-gain	Category
Interpretation	72.92	92.71	0.73	High
Analysis	57.81	94.27	0.86	High
Inference	33.68	92.19	0.88	High
Evaluation	26.04	89.06	0.85	High
Explanation	43.23	94.27	0.90	High

Table 24 N-gain data of class C

Indicator	Pre-test	Post-test	N-gain	Category
Interpretation	57.25	97.83	0.95	High
Analysis	27.54	84.06	0.78	High
Inference	28.26	90.82	0.87	High
Evaluation	39.13	88.41	0.81	High
Explanation	43.23	94.27	0.90	High

through activities: (1) understanding the meaning of phenomena (sub skill: clarifying meaning); (2) formulating problems (sub skill: decoding); (3) designing experiments by writing down tools, materials, and experimental procedures (sub skill: clarifying meaning); (4) writing down experimental data in the observation table (sub skill: expressing meaning). The interpretation indicator in the limited trial and broad trial of class B received a lower N-gain score than other indicators because students still had difficulty formulating problems based on the given phenomena.

Analysis is the ability of learners to identify actual relationships and draw conclusions from relationships among statements, questions, concepts, descriptions, or other forms that express beliefs, judgments, experiences, reasons, information, or opinions. Sub-skills: testing data, identifying data, and analyzing data (Facione, 2015). In the learning devices developed, the ability to analyze is trained through activities that require analyzing experimental results using questions provided in data analysis activities (sub-skills: data analysis). The analysis indicator in both the limited and broad trials of class C received relatively low N-gain scores compared to other indicators. This is because analyzing activities requires a deep understanding and skills in processing and interpreting data, which remains a challenge for students.

Inference is the ability to draw conclusions based on facts, evidence, or existing information that involves the ability to make predictions or logical assumptions—sub-skills: making hypotheses, questioning facts, and concluding (Facione, 2015). In the learning devices developed, inference skills are trained through activities: (1) making hypotheses based on the given phenomenon (sub skill: making hypotheses); and (2) making experimental conclusions (sub skill: making conclusions). The inference indicator in the limited trial received a low N-gain score compared to other indicators because students still struggled to connect the information they obtained to scientific concepts and to formulate logical, systematic conclusions.

Evaluation is the ability of learners to assess the credibility or other representations that describe perceptions, experiences, assessment situations, opinions, and to judge logically. Sub-skills: Evaluation (Facione, 2015). In the developed learning devices, the evaluation ability is trained through activities that evaluate experimental results based on answers from other groups and through discussion (sub-skill: evaluation). The evaluation indicator received a high N-gain score in both limited and extensive trials; however, some students still struggled to analyze the experiment's results due to the requirement for in-depth analysis skills and limited time.

Explanation is the ability to convey the results of thoughts or findings clearly and logically to others, which involves presenting reasons or evidence that support specific ideas or arguments. Sub-skills: stating results, explaining procedures, and presenting arguments (Facione, 2015). In the learning devices developed, evaluation skills are trained through activities: (1) presenting the results of the experimental design and discussing with other groups (sub skill: presenting arguments); and presenting the results of experiments, collecting data, analyzing data, and making conclusions presented in front of the class (sub skill: presenting arguments). The explanation indicator received a high N-gain score in both limited and extensive trials.

3.5 Advantages of Learning Devices

The acid-base learning innovation in this study focused on developing learning devices. The advantages of the learning devices developed are as follows. Teaching modules, as a teacher's guide to learning with a green chemistry approach and a problem-based learning model, have the advantage of instilling environmental awareness while improving students' critical thinking skills through investigation and practical experience. This aligns with Susanti's (2022) findings, which suggest that developing practicum modules grounded in green chemistry can enhance students' environmental awareness and improve their critical thinking about the environmental impact of an activity.

The Worksheet on acid-base, with a green chemistry approach and a problem-based learning model, is systematically designed to guide students through each step of the scientific method —from problem formulation and hypothesis formulation to experimental design, data collection, analysis, and conclusion. The printed worksheet format allows learners to take notes directly and organize information with more focus, without being distracted by digital devices. Relevant to the research by Jati et al. (2024), printed worksheets are teaching materials often used in classroom instruction because they are easier for students to apply and help keep them focused on learning.

The E-Module on acid-base chemistry, based on green chemistry principles and a problem-based learning model, offers advantages in flexibility and multimedia integration that support interactive learning. The material is presented in clear language and includes videos, animations, and simulations that help concretize abstract concepts and facilitate independent understanding. The digital format enables learners to access the material anytime, anywhere, thereby supporting independent and continuous learning. Relevant to the research by Amalia and Sujatmiko (2022), the advantage of e-modules is that they can be accessed anytime, anywhere, and by anyone, thereby facilitating learning for both educators and students. Other advantages include cost-effective budgeting, durability, and efficiency for portability.

4. CONCLUSION

Based on the analysis and discussion of acid-base learning innovations, it can be concluded that the development of learning devices using a green chemistry approach, combined with a problem-based learning model, aims to improve students' critical thinking skills. The learning device was deemed valid, with a mode score of 4, based on content and construction criteria. Learning devices are deemed practical for learning implementation, learner activities, and learner responses, achieving excellent results in both limited and broad trials, thereby supporting their practicality. The learning device is deemed adequate based on the significant difference between the pretest and posttest results, as determined by the Wilcoxon test. The increase in pretest and posttest critical thinking skills resulted in an N-gain score ranging from 0.35 to 1.00, indicating medium to high gains. Based on the results of validity, practicality, and effectiveness, learning devices are selected that are feasible to use and support innovation in acid-base learning.

ACKNOWLEDGMENT

D. C. A. conducted research at MA Burhanul Hidayah and drafted the article; H. N. guided and reviewed the manuscript, and validated the instrument; S. guided and validated the instrument. All authors have read and approved the published version of the manuscript. The authors would like to thank Surabaya State University and the teachers and students of MA Burhanul Hidayah for their contributions to this research.

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