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Development of STEM-PjBL Digital Learning Material Integrated with Mandailing Ethnoscience for Developing Students' Critical Thinking Skills

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Abstract: *Chemistry learning requires learning materials that connect chemical concepts with authentic contexts while developing students' higher-order thinking skills. This study aimed to develop digital learning material based on Science, Technology, Engineering, and Mathematics–Project-Based Learning (STEM-PjBL) integrated with Mandailing ethnoscience for acid–base solution learning and to determine its validity, practicality, and potential to support students' critical thinking skills. The study employed a Research and Development (R&D) design using the ADDIE model. The product was validated by three material experts and three media experts and tested with two lecturers and 30 Grade XI students at SMA Negeri 5 Medan using a one-group pretest–posttest design. Data were collected through validation sheets, practicality questionnaires, and critical-thinking tests. The results showed an overall validity of 98.58% and practicality of 98.91%. Students' critical-thinking scores increased from 32 to 88, with an N-gain of 0.82, categorized as high. Analysis and inference showed the highest N-gain (1.00), while interpretation showed the lowest (0.67). The findings indicate that the developed digital learning material is highly feasible and practical and shows potential to support critical-thinking development. However, the observed gain cannot be interpreted as causal evidence because no comparison group was included.*

Keywords: *digital learning material; STEM-PjBL; Mandailing ethnoscience; ADDIE; critical thinking*

INTRODUCTION

Chemistry education is not only aimed at developing students' conceptual understanding but also at fostering higher-order thinking skills, particularly critical thinking skills in analysing information, evaluating evidence, and solving problems. However, chemistry instruction still faces challenges in connecting abstract concepts with real-world problems. These challenges are evident in acid–base solution topics, where students are required to understand relationships among macroscopic, microscopic, and symbolic representations. Previous research has shown that contextual learning can support students' critical thinking skills (Arwin et al., 2025). STEM-oriented project learning has also been reported to support higher-order cognitive processes, including creative thinking and scientific reasoning (Yoon et al., 2023). These findings indicate that chemistry learning materials should provide opportunities for

authentic engagement, analysis, and explanation. The initial observation indicated that existing learning materials had not integrated Mandailing culture, project-based learning was not yet optimal, and student engagement remained relatively low.

One approach that may address these challenges is the integration of Science, Technology, Engineering, and Mathematics (STEM) with Project-Based Learning (PjBL). Previous studies have reported that PjBL-STEM can support student engagement, scientific literacy, and learning outcomes (Auliyani et al., 2024; Kurniasari et al., 2023). In chemistry education, STEM-PjBL-based modules have been reported to support scientific literacy and learning motivation (Dibyantini et al., 2023), while PjBL-STEM has been associated with critical-thinking development (Herlita et al., 2023). Yoon et al. (2023) also reported that STEM project-based learning supported creative thinking and scientific reasoning in university education. Collectively, these studies establish the relevance of STEM-PjBL for higher-order learning, while the present study examines its integration with Mandailing ethnoscience in acid–base chemistry.

Ethnoscience can connect community knowledge and practices with scientific concepts, making learning more contextual and relevant to students' environments (Sari et al., 2023). Previous Indonesian studies have examined local wisdom and ethnoscience-based learning materials (Sihombing et al., 2021; Ndapa et al., 2023; Amalina et al., 2024). Yuliani et al. (2023), for example, developed an ethnoscience-based e-module for acid and base topics. Thus, previous research supports STEM-PjBL, ethnoscience, and digital chemistry learning materials individually; however, their integration into one product for acid–base learning and critical-thinking development remains less documented.

The research gap therefore concerns both integration and cultural context. Existing studies have generally examined STEM-PjBL, ethnoscience-based materials, or acid–base e-modules as separate innovations. A single digital learning material that simultaneously integrates STEM-PjBL, Mandailing ethnoscience, acid–base solution content, and critical-thinking activities is less documented in the literature reviewed for this study. The present study uses Mandailing cultural phenomena as authentic contexts for chemistry problems and project activities rather than as supplementary illustrations.

The contribution of this study is the development of a digital learning material that integrates STEM-PjBL and Mandailing ethnoscience in acid–base solution learning, with an explicit orientation toward students' critical-thinking skills. The novelty claimed is therefore the integration of these components into one contextual chemistry learning resource, rather than the independent use of STEM-PjBL, ethnoscience, or digital materials.

The teaching material was developed using the ADDIE model. Accordingly, this study had three objectives: (1) to develop a digital learning material based on STEM-PjBL integrated with Mandailing ethnoscience for acid–base solution learning; (2) to determine its validity and practicality; and (3) to examine observed improvement in students' critical-thinking skills using pretest and posttest N-gain. Because the implementation used a one-group pretest–posttest design, the third objective concerns observed improvement rather than causal effectiveness.

LITERATURE REVIEW

STEM-Project Based Learning

STEM integrates science, technology, engineering, and mathematics to address problems. When integrated with Project-Based Learning (PjBL), students can apply knowledge from different disciplines while planning, implementing, testing, and evaluating project solutions. Previous research indicates that PjBL-STEM can support learning processes and outcomes, although implementation depends on planning, time, facilities, and assessment

(Auliyani et al., 2024). Kurniasari et al. (2023) reported support for scientific literacy and learning activities, while Dibyantini et al. (2023) reported support for scientific literacy and motivation. Herlita et al. (2023) examined critical thinking in PjBL-STEM, and Yoon et al. (2023) reported support for creative thinking and scientific reasoning. These studies provide a basis for STEM-PjBL as an active, higher-order learning framework, but they do not address the specific integration of Mandailing ethnoscience into an acid–base digital learning material.

Ethnoscience in Chemistry Education

Ethnoscience is an approach that connects knowledge and practices developed within a community with scientific concepts. The integration of ethnoscience into learning allows students to study science through phenomena that are closely related to their social and cultural environment. Therefore, scientific concepts are not learned separately from everyday life but are constructed through observation and interpretation of phenomena that are familiar to students. Sari et al. (2023) showed that ethnoscience studies in science education have the potential to connect local knowledge with scientific knowledge. Similarly, Sihombing et al. (2021) emphasised the importance of local wisdom in science education as a context that can strengthen the relationship between learning and students' cultural and environmental backgrounds. In chemistry education, the ethnoscience approach has been applied in the development of various learning materials. Ndapa et al. (2023) developed an ethnoscience-integrated chemistry e-module, while Yuliani et al. (2023) developed an ethnoscience-based e-module for acid and base topics. These findings indicate that ethnoscience is relevant as a contextual approach in chemistry education, including in the teaching of acid–base solutions.

In this study, ethnoscience focuses on Mandailing culture as a learning context. The integration of local culture is intended to help students connect chemistry concepts with phenomena found in their cultural environment. Ethnoscience is not positioned merely as additional information in the learning material, but as a context for presenting authentic problems that are subsequently explored through STEM-PjBL activities. This integration is expected to make chemistry learning more meaningful while also providing opportunities for students to develop critical thinking skills through culturally relevant project activities.

Digital Teaching Materials

Digital learning materials are learning resources presented in digital formats that may include text, images, videos, animations, hyperlinks, and interactive activities. The use of digital learning materials provides opportunities to present chemistry concepts in a more visual and multimodal way, which can help students understand abstract concepts. In project-based learning, digital learning materials can also function as both information sources and guides for students during the project implementation process.

The development of STEM-PjBL-based digital learning materials has received empirical support from previous research. Dibyantini et al. (2023) reported that a STEM-PjBL-based chemistry module could be used to improve students' scientific literacy and learning motivation. This finding indicates that learning materials can serve not only as sources of subject knowledge but also as tools for integrating learning approaches with activities that develop students' skills. In this study, the digital learning material is developed not merely as an electronic version of printed material, but as an integrated learning resource. It combines acid–base solution concepts, STEM-PjBL activities, Mandailing ethnoscience contexts, and learning activities designed to facilitate students' critical thinking skills. Through this integration, the digital learning material is expected to provide students with a more

contextual, active, and meaningful chemistry learning experience.

Acid–Base Solutions

Acid–base solutions are an important topic in chemistry that is relatively abstract and requires students to understand the relationships among macroscopic phenomena, microscopic representations, and symbolic representations. Learning this topic cannot rely only on memorising definitions or applying formulas. Students need opportunities to observe phenomena, analyse the properties of solutions, interpret data, and relate their observations to scientific concepts.

These characteristics make acid–base solutions suitable for learning through project-based approaches and ethnoscience contexts. Phenomena related to acid–base properties can be used as starting points for learning problems. Students can then be guided to conduct investigations and develop solutions or products through STEM-PjBL activities. The use of local contexts can also help students connect abstract concepts with their own experiences, making chemistry learning more meaningful and relevant.

Integration of STEM-PjBL, Ethnoscience, and Critical Thinking Skills

STEM-PjBL and ethnoscience serve complementary roles: ethnoscience supplies an authentic cultural context, PjBL structures investigation and product development, and STEM provides a framework for integrating disciplinary knowledge. These components can be linked to critical-thinking processes such as information analysis, evidence evaluation, inference, explanation, and conclusion drawing. Previous studies support the individual relevance of these components (Dibyantini et al., 2023; Herlita et al., 2023; Sari et al., 2023), while the present study examines their integration within one digital resource for acid–base learning.

This relationship is supported by Herlita et al. (2023), who reported the effectiveness of STEM-PjBL in developing students' critical thinking skills. Similarly, Dibyantini et al. (2023) demonstrated the potential of STEM-PjBL-based modules to improve students' scientific literacy and learning motivation. The integration of an ethnoscience context can further provide a contextual dimension that strengthens the connection between chemistry concepts and students' everyday lives. Based on this theoretical foundation, the learning material developed in this study is designed as digital learning material based on STEM-PjBL and integrated with Mandailing ethnoscience for acid–base solution learning. The product is expected to serve as a learning resource that integrates chemistry concepts, digital technology, project activities, and local culture while facilitating the development of students' critical thinking skills.

METHODS

Research Design

This study employed a Research and Development (R&D) design to develop a digital learning material based on STEM-PjBL integrated with Mandailing ethnoscience for acid–base solution learning. Product development followed the ADDIE model: Analysis, Design, Development, Implementation, and Evaluation. The model provides a systematic sequence for needs analysis, product design, development, implementation, and evaluation, with opportunities for revision at each stage (Latip, 2022; Lestari et al., 2024).

Analysis Stage

The analysis stage was conducted to identify the needs for developing the digital learning material. The analysis covered learning needs, student characteristics, curriculum requirements, acid–base solution material, and relevant aspects of Mandailing ethnoscience that could be integrated into the learning process. The needs analysis was conducted through classroom observations and an examination of the learning materials

currently used. The findings from this stage were used as the basis for determining the characteristics of the learning material, STEM-PjBL activities, Mandailing ethnoscience context, and critical thinking indicators to be facilitated through the product.

Design Stage

The design stage was carried out based on the results of the needs analysis. At this stage, the structure and content of the digital learning material, learning objectives, acid–base solution material, STEM-PjBL activities, Mandailing ethnoscience context, and research instruments were designed. The learning material was designed so that the learning activities followed a project-based learning approach and integrated the elements of Science, Technology, Engineering, and Mathematics. At this stage, a project-based student worksheet (LKPD), validation sheets, practicality questionnaires, critical thinking skills tests, and observation sheets were also prepared. The systematic design of the learning material using the ADDIE model is consistent with its application in the development of multimedia and instructional textbooks (Latip, 2022; Lestari et al., 2024).

Development Stage

The development stage was conducted by transforming the design into a prototype of digital learning material based on STEM-PjBL integrated with Mandailing ethnoscience. The product was then validated by material, media, and language experts using validation sheets. The validation results were analysed to determine the feasibility of the product and were used as the basis for revision. After revision, the product was prepared for the trial stage.

Implementation Stage

The Implementation stage was conducted through a limited trial involving 30 Grade XI students at SMA Negeri 5 Medan. The study used a pre-experimental one-group pretest–posttest design. Two lecturers participated as product users in the practicality assessment. The procedure was chronological: (1) critical-thinking pretest; (2) STEM-PjBL learning using the digital learning material integrated with Mandailing ethnoscience; (3) observation of the learning process; (4) posttest; and (5) practicality questionnaires for the two lecturers and 30 students.

Evaluation Stage

Evaluation was conducted through formative and summative evaluation. Formative evaluation was carried out at each development stage through product revision based on the results of analysis and validation. Summative evaluation was conducted to determine the overall quality of the learning material based on its validity, practicality, and effectiveness. Practicality was determined from user responses and the implementation of the learning process, while effectiveness was determined from the improvement in students' critical thinking skills based on their pretest and posttest scores.

Research Instruments

The research instruments consisted of expert validation sheets, practicality questionnaires, a critical-thinking test, and a learning-observation sheet. The material-validation instrument contained 12 items scored on a 1–4 Likert scale, and the media-validation instrument contained 22 items scored on the same scale. The practicality questionnaire assessed ease of use, clarity of instructions, readability, visual attractiveness, ease of STEM-PjBL implementation, and meaningfulness of the Mandailing ethnoscientific context. The critical-thinking test used five indicators adapted from Reynders et al. (2019): interpretation, analysis, evaluation, inference, and explanation. The manuscript did not report an empirical reliability coefficient; therefore, no reliability value is added here. If reliability evidence was

obtained, it should be inserted by the authors before submission.

Validity was calculated as V = (ΣX/ΣXmax) × 100%. Practicality was calculated from the mean user score on the 1–4 scale. The overall practicality was recalculated using a respondent-weighted mean: [(2 × 3.90) + (30 × 3.96)]/32 = 3.95625, corresponding to 98.91% of the maximum score. N-gain was calculated as g = (posttest − pretest)/(maximum score − pretest). For the overall critical-thinking score, g = (88 − 32)/(100 − 32) = 0.82. Ethical approval/informed-consent details were not reported in the source manuscript and should be completed by the authors if applicable.

RESULT AND DISCUSSION

The research findings are presented according to the development stages of the ADDIE model, namely Analysis, Design, Development, Implementation, and Evaluation. This presentation illustrates the development process of a digital learning material based on Science, Technology, Engineering, and Mathematics–Project-Based Learning (STEM-PjBL) integrated with Mandailing ethnoscience for the topic of acid–base solutions.

1. Analysis Stage

The Analysis stage was conducted to identify the needs for developing digital learning materials, students' characteristics, the curriculum, the acid–base solution topic, and the potential of relevant Mandailing ethnoscience to be integrated into the learning process. The findings from this analysis served as the basis for determining the characteristics of the learning materials, STEM-PjBL activities, ethnoscientific contexts, and indicators of critical thinking skills to be developed (Latip, 2022; Lestari et al., 2024).

The analysis indicated that the acid–base solution topic requires learning materials that connect macroscopic, microscopic, and symbolic representations. The use of ethnoscientific contexts can strengthen the connection between chemical concepts and students' everyday lives, thereby making learning more meaningful and contextual (Sari et al., 2023; Yuliani et al., 2023).

The potential of Mandailing culture was identified through local food-related phenomena, such as sambal tuk-tuk and daun ubi tumbuk. Ethnoscience was positioned as an authentic context for presenting real-life problems that could subsequently be explored through project-based learning activities (Sihombing et al., 2021; Yuliani et al., 2023).

2. Design Stage

The Design stage was conducted based on the findings of the needs analysis. At this stage, the structure and content of the digital learning materials, learning objectives, acid–base solution topic, STEM-PjBL activities, Mandailing ethnoscience context, and research instruments were designed. The learning materials were developed by integrating Science, Technology, Engineering, and Mathematics (STEM) components (Auliyani et al., 2024; Kurniasari et al., 2023).

The product consists of learning objectives, learning materials, a concept map, project activities, student worksheets (Lembar Kerja Peserta Didik/LKPD), summaries, competency tests, a glossary, and references. The project activities were designed to guide students through problem identification, information gathering, data processing, solution design, testing, evaluation, and presentation of the results (Dibyantini et al., 2023; Herlita et al., 2023).

The research instruments developed at this stage included an expert validation sheet, practicality questionnaire, critical thinking skills test, and learning observation sheet. The critical thinking skills instrument was supported by the framework proposed by Reynders et al. (2019).

3. Development Stage

The Development stage involved transforming the design into a prototype of the

digital learning material based on STEM-PjBL integrated with Mandailing ethnoscience. The product was validated by subject-matter and media experts. The validation results were used to determine the feasibility of the product and served as the basis for revision before the product was subjected to the trial stage.

3.1 Expert Validation of Learning Materials

The validation was conducted by three expert validators, all of whom were lecturers in the Department of Chemistry with master's degrees (S2) in Chemistry Education and Chemistry. Their expertise was considered relevant to evaluating the content quality, conceptual accuracy, and pedagogical appropriateness of the developed learning materials.

Table 1. The Results of Expert Validation of Learning Materials

Assessor	Score	Maximum Score	Percentage
Material Validator 1	47	48	97.92%
Material Validator 2	47	48	97.92%
Material Validator 3	47	48	97.92%
Average	141	144	97.92%

The material experts assigned 47 out of 48 points (97.92%) each. The 12-item instrument used a 1–4 Likert scale, giving a maximum score of 48. The result indicates strong agreement among the three validators regarding content suitability, conceptual accuracy, currency, project-based learning integration, and ethnoscience integration.

The three material validators produced the same score of 47, indicating a consistent assessment of the quality of the developed learning material. The very high validity percentage indicates that the material components, including content suitability, conceptual accuracy, currency of the material, integration of Project-Based Learning, and ethnoscience, meet the criteria for a highly feasible learning material. The high validation score also indicates that the acid–base solution content, project activities, and ethnoscientific context are appropriately aligned with the intended learning objectives.

From a theoretical perspective, the alignment among learning objectives, content, learning activities, and contextual elements is essential to ensure that learning materials can facilitate learning in a systematic and meaningful manner. In the present study, the empirical evidence represented by the 97.92% validity score supports the suitability of the material design with the requirements of the developed product.

The material-validity result is consistent with studies showing that ethnoscience can connect chemistry concepts with everyday contexts (Sari et al., 2023; Yuliani et al., 2023) and with research on STEM-PjBL chemistry learning materials (Dibyantini et al., 2023). The present contribution is more specific: Mandailing cultural phenomena are integrated with STEM-PjBL within an acid–base digital learning material. The validation result supports feasibility, but it does not demonstrate that the cultural integration caused the high score.

The validity percentage was calculated using the following equation:

$$V = (\Sigma X / \Sigma X_{max}) \times 100\%$$

Table 2. The Average Scores of Material Expert Validation by Aspect

Aspect	Number of Items	Average Score/Item
Material suitability	3	4.00
Material accuracy	2	3.83
Material currency	2	4.00
Project-Based Learning	3	3.92
Ethnoscience integration	2	4.00

The results of the material expert validation indicate that the aspects of material suitability, material currency, and ethnoscience integration each obtained the highest average score of 4.00. The material

accuracy aspect obtained an average score of 3.83, while the Project-Based Learning aspect obtained an average score of 3.92. These results indicate that all assessed components of the learning material achieved a high level of feasibility.

The material suitability score of 4.00 indicates that the content is considered appropriate in relation to the intended learning objectives and the acid–base solution topic. Similarly, the material currency score of 4.00 indicates that the content presented is sufficiently up to date and relevant to the learning objectives. The ethnoscience integration aspect also obtained the maximum average score of 4.00, indicating that the integration of Mandailing ethnoscience was considered appropriate within the developed learning material.

The material accuracy aspect obtained a slightly lower average score of 3.83, although it remained within the high feasibility level. This finding indicates that the concepts presented in the learning material were considered accurate and appropriate, while minor improvements may still be possible in the presentation of certain chemical concepts. Meanwhile, the Project-Based Learning aspect obtained an average score of 3.92, indicating that the project activities were appropriately incorporated into the learning material and were relevant to the intended learning objectives.

The high score for ethnoscience integration indicates that local cultural contexts can strengthen the connection between chemical concepts and phenomena encountered in students' surroundings. This finding is consistent with Sari et al. (2023) and Sihombing et al. (2021), who emphasize the potential of ethnoscience and local wisdom to connect scientific knowledge with students' cultural and environmental contexts. In the present study, the integration of Mandailing ethnoscience provides a contextual dimension to acid–base learning while supporting the implementation of project-based activities.

3.2 Media Expert Validation

The three media validators obtained 87, 87, and 88 out of 88 points, corresponding to 98.86%, 98.86%, and 100.00%, with a mean of 99.24%. The 22-item media instrument used a 1–4 Likert scale. These results indicate positive assessment of the product's structure, layout, readability, illustrations, presentation, and navigation.

Table 3. Results of Media Expert Validation

Assessor	Score	Maximum Score	Percentage
Media Validator 1	87	88	98.86%
Media Validator 2	87	88	98.86%
Media Validator 3	88	88	100.00%
Average	262	264	99.24%

The media result is relevant to project-based learning because students need to access instructions and interconnected activities systematically. Previous research similarly emphasizes usability and presentation quality in digital learning-material development (Lestari et al., 2024; Dibyantini et al., 2023). The very high score should nevertheless be interpreted as perceived product feasibility rather than learning effectiveness.

The media validity score of 99.24% therefore provides empirical evidence that the technical and presentation aspects of the developed product are highly appropriate for its intended purpose. The result is consistent with previous studies on digital learning material development and STEM-PjBL, which emphasize the importance of presentation quality and ease of use as essential components of product feasibility (Lestari et al., 2024; Dibyantini et al., 2023). Thus, the high media validation score supports the readiness of the digital learning material to proceed to the implementation stage.

3.3 Validity Recapitulation

Material experts' mean validity was 97.92% and media experts' mean validity was 99.24%, producing an overall validity of 98.58% based on the mean of the two expert-group percentages. The result indicates that the developed product was considered highly feasible in terms of content and media presentation.

These findings provide evidence that the developed product meets the feasibility criteria from two main aspects: content quality and media quality. The high validity score can be attributed to the alignment among the acid–base solution content, STEM-PjBL activities, ethnoscientific context, and systematic digital presentation. Such alignment is important because the learning material is not only expected to present chemically accurate concepts but also to facilitate the implementation of project-based learning activities.

The results are consistent with previous studies on STEM-PjBL and context-based learning material development, which emphasize the importance of integrating content, learning activities, and media presentation in producing feasible learning resources (Dibyantini et al., 2023; Herlita et al., 2023; Lestari et al., 2024). The present findings therefore reinforce previous research while providing a distinctive contribution through the integration of Mandailing ethnoscience into a digital STEM-PjBL learning material for acid–base solution topics.

Overall, the validity results indicate that the developed digital learning material is sufficiently feasible to proceed to the subsequent implementation stage. The combination of very high content and media validity also suggests that the product has been appropriately designed to support contextual, project-based, and STEM-oriented chemistry learning.

Table 4. Validity Recapitulation of Material and Media Experts

Component	Average Percentage	Category
Material experts	97.92%	Very valid
Media experts	99.24%	Very valid
Overall	98.58%	Very valid

3.4 Validator Feedback and Product Revision

Validator feedback focused on alignment among learning objectives, content, project activities, cultural context, visual presentation, and language. The product was revised before implementation. Revisions strengthened the relationship between Mandailing cultural phenomena and acid–base concepts, added analysis and evaluation questions, and improved layout, illustrations, navigation, and language. These changes were intended to improve alignment and usability, not to establish a causal relationship with later learning gains.

The revisions made to the learning objectives and project activities ensured that each project directly supported the intended learning outcomes. Strengthening the connection between Mandailing cultural phenomena and acid–base concepts also enhanced the contextual nature of the learning material by helping students relate chemical concepts to familiar cultural practices.

Furthermore, the addition of analysis and evaluation questions reinforced the product's orientation toward developing students' critical thinking skills. These revisions are consistent with the findings of Herlita et al. (2023), who reported that STEM-PjBL learning environments are more effective in promoting higher-order thinking when students are actively engaged in analysing problems, evaluating evidence, and proposing solutions.

The improvements to layout, illustrations, navigation, and language also enhanced the readability and usability of the

digital learning material. As a result, the revised product became more systematic, user-friendly, and suitable for supporting the implementation of contextual STEM-PjBL learning integrated with Mandailing ethnoscience.

4. Implementation Stage

The limited trial involved 30 Grade XI students at SMA Negeri 5 Medan, while two lecturers participated as product users. The one-group pretest–posttest procedure consisted of a pretest, STEM-PjBL learning using the Mandailing-ethnoscience digital learning material, learning-process observation, a posttest, and practicality questionnaires for lecturers and students.

4.1 Practicality of the Learning Material

Table 5. Results of the Practicality Assessment

Respondent	Number	Average Score	Percentage
Lecturers	2	3.90	97.50%
Students	30	3.96	99.00%
Overall	32	3.96	98.91%

Practicality was assessed using a 1–4 Likert-scale questionnaire. The two lecturers had a mean score of 3.90/4.00 (97.50%). The 30 students had a mean score of 3.96/4.00, corresponding to 99.00%. Using a respondent-weighted calculation, the overall mean was 3.95625/4.00, corresponding to 98.91%. This corrects the 99.04% student percentage and 98.27% overall percentage reported in the original manuscript.

The lecturers' and students' responses indicate that the product was perceived as easy to use and suitable for the planned learning activities. These values represent user perceptions of practicality and should not be interpreted as direct evidence of learning effectiveness.

The high student response may be related to the systematic organization, clear instructions, visual presentation, and contextual use of Mandailing ethnoscience. These are plausible interpretations because the design did not separately test which product feature was responsible for the response.

Overall practicality was 98.91% based on the respondent-weighted calculation. This result indicates very high perceived usability among the participating lecturers and students.

The practicality finding is consistent with the emphasis on usability and ease of implementation in learning-material development (Lestari et al., 2024) and complements research indicating that ethnoscience can make science learning more contextual (Sari et al., 2023; Yuliani et al., 2023). Table 6 presents the average practicality scores for each assessment aspect.

Table 6. Average Practicality Scores by Assessment Aspect

Aspect	Lecturers (Average)	Students (Average)
Ease of use	4.00	3.87
Clarity of instructions	4.00	3.83
Readability of the material	3.50	3.87
Visual attractiveness	3.50	3.90
Ease of STEM-PjBL activities	3.50	3.83
Meaningfulness of ethnoscience	4.00	3.93

The aspect-level results indicate that practicality was related not only to visual presentation but also to users' ability to follow learning activities and understand relationships between chemical concepts and the cultural context. The meaningfulness ratings suggest that Mandailing cultural contexts were accepted as an integral part of the learning material, although they do not establish that the cultural context caused the high practicality ratings.

4.2 Improvement in Critical Thinking Skills

Critical-thinking performance was assessed using five indicators—interpretation, analysis, evaluation, inference, and explanation—through pretest and posttest scores. The total score increased from 32 to 88 out of 100. N-gain was calculated as g = (posttest − pretest)/(100 − pretest), yielding 0.82. The indicator-level results are presented in Table 7.

Table 7. Pretest, Posttest, and N-gain of Students' Critical Thinking Skills

Indicator	Pretest	Posttest	N-gain	Category
Interpretation	8	16	0.67	Moderate
Analysis	8	20	1.00	High
Evaluation	4	16	0.75	High
Inference	8	20	1.00	High
Explanation	4	16	0.75	High
Overall	32	88	0.82	High

All five indicators showed positive observed gains. Analysis and inference each reached 1.00; evaluation and explanation reached 0.75; and interpretation reached 0.67. The pattern should be interpreted as an observed pretest–posttest change within the limited trial, not as a causal effect of the learning material.

The N-gain of 1.00 for analysis may be associated with project activities requiring students to identify relevant information, examine relationships among data, conduct investigations, and use evidence to develop solutions (Auliyani et al., 2024). Because no comparison group was used, alternative explanations such as prior knowledge or testing effects cannot be excluded.

Inference also reached 1.00. The project sequence required students to use observations and investigation results when formulating conclusions, which may be associated with the observed improvement. Herlita et al. (2023) likewise reported positive critical-thinking outcomes in a PjBL-STEM context. The present study cannot isolate the contribution of STEM-PjBL from ethnoscience, the digital format, or repeated exposure to assessment.

Evaluation and explanation each showed an N-gain of 0.75. Project activities required students to compare alternatives, assess results, and communicate reasoning. These activities may have contributed to the observed gains, although the design does not permit attribution to a single instructional component.

Interpretation had the lowest N-gain (0.67), suggesting that interpreting data, problems, or situations remained comparatively more challenging. Interpretation may require students to coordinate information across images, tables, phenomena, and macroscopic, microscopic, and symbolic representations. Future iterations could provide more graduated interpretation prompts. Contextual learning may also support this process (Arwin et al., 2025).

Overall, the N-gain of 0.82 indicates substantial observed improvement in critical-thinking scores during the limited trial. The integration of ethnoscience, PjBL, and STEM provides a plausible instructional rationale for authentic problem solving, but the one-group design does not establish that these components caused the gain. Future studies should use quasi-experimental or experimental designs with larger samples.

5. Evaluation Stage

The Evaluation stage combined formative and summative evaluation. Formative evaluation occurred throughout development through needs analysis, validator feedback, and product revision. Summative evaluation considered validity, practicality, and observed pretest–posttest critical-thinking gain. The results are presented separately in Figures 1 and 2 because validity/practicality percentages and N-gain values have different scales and meanings.

Figure 1. Overall Validity and Practicality of the Digital Learning Material

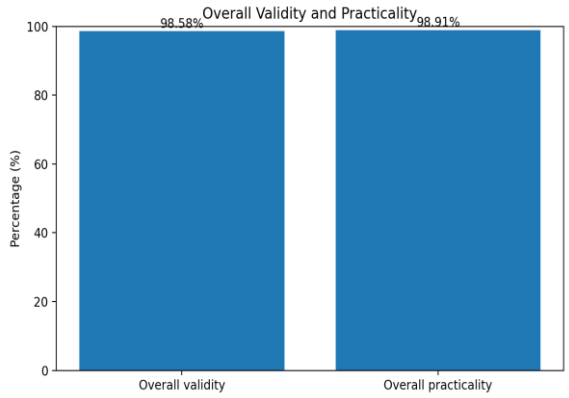
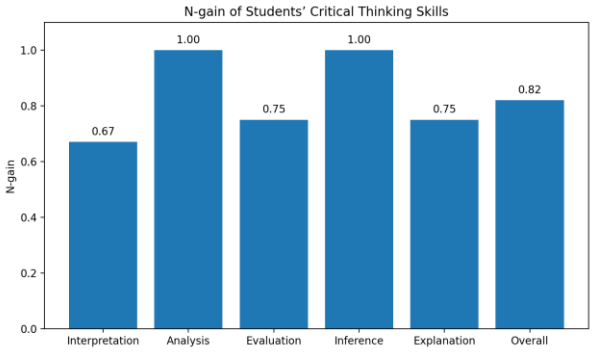


Figure 1 summarizes the two percentage-based product-quality indicators. Overall validity was 98.58%, while overall practicality was 98.91% after respondent-weighted recalculation. These values indicate perceived feasibility and usability rather than learning effectiveness.

Figure 2 presents the N-gain results separately because N-gain is not measured on the same scale as validity and practicality percentages. The overall N-gain was 0.82, with the highest indicator-level values for analysis and inference (1.00) and the lowest for interpretation (0.67).

Figure 2. N-gain of Students' Critical Thinking Skills



The high validity result suggests strong alignment among the acid–base content, learning objectives, STEM-PjBL activities, Mandailing ethnoscientific context, and media presentation. The high practicality result indicates positive user perceptions of usability. These findings are consistent with systematic development and revision within the ADDIE process (Latip, 2022; Lestari et al., 2024).

The observed N-gain suggests that students' critical-thinking scores increased after the learning sequence. The stronger gains in analysis and inference may be related to activities requiring information processing, evidence use, and conclusion drawing, whereas interpretation may require more explicit scaffolding across representations. Alternative explanations cannot be ruled out without a comparison group.

The ADDIE process provided opportunities to identify needs, design the product, obtain expert feedback, revise the material, and conduct a limited implementation. The resulting evidence supports feasibility and practical usability and indicates potential for supporting critical-thinking development. The small implementation sample and one-group design limit generalizability and causal interpretation.

The study extends previous work by integrating STEM-PjBL, Mandailing ethnoscience, and digital learning materials within one acid–base chemistry resource. The contribution is primarily developmental and contextual. The results provide preliminary evidence that can inform further testing with larger samples and stronger comparison designs.

CONCLUSION

The digital learning material based on STEM-PjBL integrated with Mandailing ethnoscience for acid–base solution learning was developed using the ADDIE model. Expert assessment yielded an overall validity of 98.58%, while the respondent-weighted practicality calculation yielded 98.91%. In the limited one-group pretest–posttest trial involving 30 Grade XI students at SMA Negeri 5 Medan, the critical-thinking score increased from 32 to 88, corresponding to an overall N-gain of 0.82. Analysis and inference showed the highest indicator-level N-gain (1.00), whereas interpretation showed the lowest (0.67). These results suggest that the developed material is feasible and practical and has

potential to support critical-thinking development. However, the absence of a control or comparison group means that the observed N-gain cannot establish a causal effect. Future research should use quasi-experimental or experimental designs with larger and more diverse samples.

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