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Development of Science Virtual Laboratory Integrated with Local Potential of Kotagede Silver Crafts to Improve Critical Thinking Skills and Learning Independence

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Abstract

This research aims to develop a virtual science laboratory integrated with the local potential of Kotagede silver crafts as an interactive learning medium and to examine its practicality and effectiveness in improving critical thinking skills and learning independence. The development used ADDIE model: Analyze, Design, Develop, Implement, and Evaluate. The analysis covered preliminary, student, curriculum, and concept. The planning stage produced a criterion-referenced test, product outline, storyboard, and virtual laboratory design. The development stage included product development, validation by three lecturers and two practitioners, and a readability test. The implementation involved empirical testing and a field trial, with evaluation at each stage. Product feasibility was analyzed using mean scores converted into a four-point scale. Trial subjects were selected through cluster random sampling. The field trial applied a nonequivalent pretest-posttest control group design with 33 students in the experimental class and 34 in the control class from a junior high school in Yogyakarta. Readability, practicality, and feasibility were measured using average percentages, while effectiveness was tested with an effect size. Results showed that the virtual science laboratory was 80.2% feasible (very good), practical for classroom use, and effective in improving critical thinking and students learning independence.

How to Cite

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INTRODUCTION

Science education in schools faces multiple challenges, including limited facilities, diverse student abilities, and curriculum demands (Darling-Hammond et al., 2020). Teachers often rely heavily on textbooks due to time constraints and limited pedagogical knowledge (Fitzgerald et al., 2019). Furthermore, the demands of the Industrial Revolution 4.0 have shifted the goals of education (Melinda & Sa'ud, 2022). To remain relevant, education must equip students with 21st-century skills (Rukmi et al., 2025), including scientific literacy, critical thinking, problem solving, communication, collaboration, creativity, and learning independence.

Critical thinking is a higher-order cognitive strategy for solving complex problems and supports both cognitive development and adaptability (Abrami et al., 2015). Its indicators include interpretation, analysis, inference, evaluation, and self-regulation (Alsaleh, 2020). Partnership for 21st Century Skills highlights critical thinking as essential for both education and the workplace (van Laar et al., 2020). However, Indonesian students still perform poorly in this domain. According to the Programme for International Student Assessment (PISA), Indonesia ranked 74th of 79 countries in literacy, mathematics, and science (Schleicher, 2018). Only about 5% of Indonesian students were able to solve higher-level reasoning tasks, indicating a low mastery of critical thinking (Rahayu, 2016).

Alongside critical thinking, learning independence is a crucial element of student success. In Indonesia, these skills are emphasized through the Profil Pelajar Pancasila framework, which includes critical reasoning and independent learning as key dimensions (Kepmendikbudristek, 2022). Independent learners take responsibility for their learning goals, manage their study time effectively, persist through challenges, and evaluate their own progress (Panadero, 2017). Research shows that learning independence influences students' achievement and innovation capacity (Broadbent & Poon, 2015). Unfortunately, recent findings indicate that learning independence among middle school students is still developing and not yet optimal, as many students continue to face difficulties in managing their learning processes (Torres et al., 2024).

The persistent lack of critical thinking and learning independence among Indonesian students highlights the need for innovation in instructional practice. Teacher-centered approaches and limited use of student-centered learning models have been identified as key barriers (Freeman et al., 2014; Hairida & Hadi, 2017). Instructional approaches strongly influence student outcomes, and the scientific approach has been shown to foster more active, two-way learning. This method has proven effective in improving both learning independence (Lazonder & Harmsen, 2016; Nahdliyati et al., 2016) and critical thinking skills (Bensley & Murtagh, 2012; García-Carmona, 2025; Lieung et al., 2020).

Science learning emphasizes direct involvement in scientific inquiry, enabling students to observe and understand natural phenomena (Cairns & Areepattamannil, 2019; Osborne, 2014). This process is best supported through hands-on and experiential learning activities that engage students in scientific practices, such as experimentation and investigation (Tindan & Anaba, 2024). Based on interviews with teachers, practical work in schools remains limited due to insufficient facilities, lack of equipment, inadequate time allocation, absence of laboratory assistants, and challenges in implementing laboratory activities effectively. Virtual laboratories provide an alternative solution by simulating experiments through computer programs. These tools enable students to explore and visualize abstract concepts (Baser & Durmus, 2010), support the development of critical thinking (Fadhilah et al., 2021; Sujono et al., 2023), and offer practical advantages such as cost-efficiency, safety, time saving, and increased learning motivation (Herga et al., 2014).

Integrating local potential into science education ensures holistic student achievement consistent with the nature of science (Latip et al., 2024; Wilujeng et al., 2017). However, a decline in younger generations' knowledge and appreciation of local culture has become a significant concern, as local cultural values are increasingly no longer reflected in adolescents' social behavior due to the influence of globalization and popular culture (Rosa et al., 2021). Indonesian educational policy explicitly encourages teachers to embed local issues in learning (Kepmendikbudristek, 2022). Local resources can thus serve as inquiry-based contexts for developing curiosity, reflection, and scientific process skills.

One prominent local potential in Yogyakarta is the Kotagede silver craft, which has been renowned since the 16th century and achieved international recognition (Birsyada & Siswanta, 2019). Findings from field interviews indicate that production has significantly declined in recent decades, leading to a reduction in the number of artisans. Despite its strong relevance to science, the silver craft industry has not been incorporated into formal science education. The processes of melting, forming, coating, soldering, assembling, and polishing inherently involve physics concepts such as heat, temperature, and thermal expansion. Nevertheless, no previous research has developed a virtual science laboratory that integrates the processes of Kotagede silver crafts as a contextual basis for science learning.

Although previous studies have demonstrated the effectiveness of virtual laboratories and the integration of local potential in science learning, these approaches are generally implemented separately and have not been specifically designed to simultaneously enhance critical thinking skills and learning independence within a single integrated framework. In addition, studies that connect virtual laboratory development with authentic local industry contexts remain limited.

Therefore, this study aims to fill this gap by developing a virtual science laboratory integrated with the local potential of Kotagede silver crafts through a scientific approach. This study offers a novel contribution by combining virtual laboratory technology and local cultural context in a single framework to simultaneously enhance students' critical thinking skills and learning independence. The study specifically seeks to address three research questions: (1) How feasible is the virtual science laboratory integrated with the local potential of Kotagede silver crafts? (2) How practical is the virtual science laboratory when implemented in classroom learning? and (3) How effective is it in enhancing students' critical thinking skills and learning independence?

METHOD

This study aims to produce a virtual laboratory application integrated with local potential, namely the silver craft of Kotagede, on the topics of temperature, heat, and expansion. The application was developed in two formats, .exe and .apk, which can be operated on both mobile devices and laptops. The research and development process followed the ADDIE model as proposed by Robert Maribe Branch, consisting of the stages Analyze, Design, Develop, Implement, and Evaluate (Figure 1).

To provide a clearer illustration of the research procedure, a flowchart based on the ADDIE model used in this study is presented in Figure 2. The analysis stage encompassed preliminary analysis, learner characteristics, curriculum analysis, and concept analysis. Preliminary information regarding the teaching and learning process, student characteristics, and curriculum implementation at the school was obtained through classroom observation and interviews with science teachers. Meanwhile, the silver craft production process was explored through observation and interviews with local artisans in Kotagede (Figure 2).

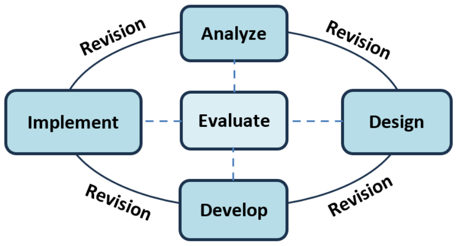

Figure 1. ADDIE Model (Branch, 2009)

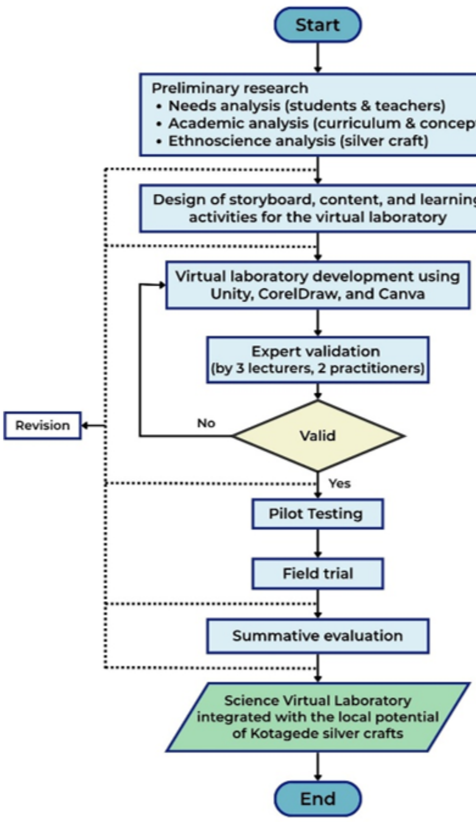

Figure 2. Product development research flowchart

The design stage involved preparing criterion-referenced tests, developing a blueprint for the virtual laboratory, creating a storyboard, and designing instructional activities using the virtual laboratory. At the development stage, the designed product was realized through the preparation of the initial prototype, expert validation, and readability testing. The prototype was developed using Corel Draw and Canva for UI/UX design, and Unity software for application flow and coding. The feasibility of the product was evaluated by five validators: three lecturers and two practitioners. The main product was the virtual laboratory application, supported by instruments to assess critical thinking skills and learning independence. These were pilot-tested with a limited number of students to examine readability, validity, and reliability.

Afterward, the implementation stage included empirical testing with 65 students and a field trial with 67 students of varying genders. The empirical test was conducted with Grade VIII students who had already studied the relevant topics, while the field trial was carried out with Grade VII students. The evaluation stage was integrated into each step of the ADDIE model through formative and summative evaluations.

Research Design

The practicality and effectiveness of the virtual laboratory were measured through field trials conducted in November, during the odd semester of the 2023/2024 academic year. Cluster random sampling was employed in selecting the subjects since most students were residents of Yogyakarta and thus familiar with the Kotagede silver craft. The field trial took place in Grade VII Semester I of one of the middle schools in Yogyakarta. Class VII B, consisting of 33 students, served as the experimental group, while Class VII A, with 34 students, acted as the control group. The research design followed a nonequivalent pretest-posttest control group structure, as shown in Table 1.

Table 1. Nonequivalent Pretest-Posttest Control Group Design

Group	Pretest	Treatment	Posttest
Eksperiment	O_1	X_1	O_2
Control	O_1	X_2	O_2

In the experimental treatment (X_1), students learned through the integrated virtual laboratory with a scientific approach. In contrast, in the control treatment (X_2), instruction was delivered using PowerPoint with approaches other than the scientific method. The results were analyzed using SPSS, and the effectiveness of both methods was compared.

Data Collection Techniques

Questionnaires were employed to evaluate the practicality of the virtual laboratory and students' learning independence. Interviews and observations were conducted during the preliminary analysis to identify learning problems and document the silver craft-making process. Tests and observations were also used to measure students' critical thinking skills and learning independence. Research instruments included interview guidelines, student needs questionnaires, expert validation sheets, student readability questionnaires, and teacher practicality sheets. In addition, critical thinking tests and independence questionnaires were developed to assess product effectiveness.

The feasibility and practicality of the product were analyzed by calculating the mean score and converting it into a four-point scale based on Mardapi's criteria, as presented in Table 2.

Table 2. Score Conversion to 4-Point Scale

Score Range	Grade	Category
$X > X, + 1.50$ SBi	A	Very Good
$X, + 1.50$ SBi $> X \geq X,$	B	Good
$X, > X \geq X, - 1.50$ SBi	C	Fair
$X, - 1.50$ SBi $> X$	D	Poor

The conversion was carried out by first calculating the ideal mean ($X,$), defined as half the sum of the maximum and minimum ideal scores. The ideal standard deviation (SBi) was determined as one-sixth of the difference between the maximum and minimum ideal scores. The maximum ideal score is obtained from the total number of items multiplied by the highest score, while the minimum ideal score is derived from the total number of items multiplied by the lowest score. Instrument validation was analyzed using Aiken's V formula.

$$V = \frac{\Sigma S}{n(c-1)}$$

Each item was reviewed in terms of content, construction, and language. With four categories and five raters, an item was considered valid if $V \geq 0.87$ (Aiken, 1985). The construct validity results were further compared with the Aiken's V criteria, as shown in Table 3.

Table 3. Aiken's V Validity Criteria

Validity Coefficient	Category
$0.75 \leq V \leq 100$	Highly valid
$0.50 \leq V < 0.75$	Acceptably valid
$0.25 \leq V < 0.50$	Less valid
$0.00 \leq V < 0.25$	Not valid

Empirical validity was examined using QUEST software to evaluate item validity, reliability, and difficulty. Critical thinking was measured with multiple-choice items requiring reasoning, while learning independence was measured with a questionnaire. Items with Infit MNSQ values between 0.77-1.33 were considered valid (Neumann et al., 2011). Instrument reliability with coefficients above 0.80 categorized as highly reliable (Taber, 2018).

Data Analysis

Effectiveness was further analyzed using effect size, based on partial eta squared (ηp^2).Prior to effectiveness testing, the data were subjected to prerequisite analyses including normalized gain, univariate and multivariate normality, homogeneity of variance and covariance, linearity, multicollinearity, and MANOVA.

Further analysis of product effectiveness employed Multivariate Analysis of Variance (MANOVA). This method was used to compare students' critical thinking skills and learning independence between the experimental and control groups. To ensure accurate results, several prerequisites were tested. The equality of the initial conditions between the groups was first examined using one-way ANOVA.

The MANOVA assumptions were then verified, including the requirement of interval or ratio data, the presence of at least two dependent variables, independence of measurements, an adequate number of subjects, and the absence of outliers. Normality was tested both univariately (Shapiro-Wilk) and multivariately, while linearity between dependent variables was confirmed through linearity tests. Homogeneity of variance and covariance was assessed using Levene's test and Box's M test, and multicollinearity was checked using tolerance and VIF values. Only after all assumptions were satisfied was MANOVA conducted.

The MANOVA analysis examined three levels of hypotheses. The first hypothesis tested whether there were overall differences in students' critical thinking and learning independence between the experimental and control groups, evaluated using Hotelling's Trace. If significant differences were detected, follow-up univariate tests were performed. The second hypothesis examined differences for each dependent variable individually, applying the Greenhouse–Geisser correction. The third hypothesis investigated whether there were significant mean improvements in pretest–posttest scores for both variables across the groups, which was analyzed through Pairwise Comparisons.

The effectiveness of the product was determined using effect size analysis This step provided insights into the practical significance of the intervention in enhancing students' critical thinking and learning independence. Following Cohen (1988) in Lakens (2013), $\eta^2 < 0.06$ indicated a small effect, 0.06-0.14 a moderate effect, and >0.14 a large effect.

Table 4. Effect Size Interpretation (η^2)

Partial Eta Squared (η^2)	Effect size
< 0.06	Small effect
0.06-0.014	Moderate effect
>0.14	Large effect

RESULT AND DISCUSSION

Results analysis in the define stage show that the science learning environment of the middle school is located near Kotagede, which is well known for its traditional silver crafts. However, classroom observations revealed that many students were not familiar with this cultural heritage and that science lessons, especially in heat, temperature, and expansion topics, often lacked experimental activities. Teachers usually relied on demonstrations due to limited laboratory facilities, leading to reduced student engagement and low learning outcomes, with many students scoring below the minimum standard.

Further analysis through interviews with silver artisans identified that the production process of Kotagede silver, such as melting, mixing with copper, forming, soldering, cleaning, and polishing directly relates to physics concepts. Teachers expressed interest in integrating these processes into learning media but lacked appropriate tools. The student needs survey confirmed this gap: 78.8% of students preferred lessons connected to local potential, 75.8% wanted laboratory practice, and 93.9% were interested in virtual laboratory activities. In addition, most students owned smartphones. This condition shows that developing a digital learning medium is relevant.

The second stage in the design process involved drafting research instruments, product blueprints, and a storyboard. The application was planned to contain login menus, learning objectives, concept maps, materials, virtual experiments, and evaluation features. The learning flow was arranged according to the scientific approach, consisting of observing, questioning, hypothesizing, collecting data, analyzing, concluding, and communicating.

The third stage in product development resulted in a prototype called Virtual Lab Perak. The application was built using Unity software, while the user interface and graphic elements were designed using Corel Draw and Canva. Unity was chosen because it offers advantages over other software, namely ability to develop both 2D and 3D applications, including complex simulations, smartphone and laptop applications, websites, and other platforms (Radianti et al., 2020). The prototype was produced in both .apk and .exe formats to ensure accessibility on smartphones and laptops. The application contains several main menus, including a cover page, login page, main menu, competencies, concept map, learning materials, virtual experiments, evaluation questions, user guide, and developer profile.

The virtual experiment section consists of three types of experiments related to the science topics of heat, calorimetry, and thermal expansion. These experiments were designed to be implemented sequentially across three meetings. Each experiment allows students to manipulate variables, observe phenomena, collect and analyze data, and draw conclusions within a simulated environment. The display of the virtual laboratory can be seen in the following figures.

Figure 3. Login page

Figure 4. App menu

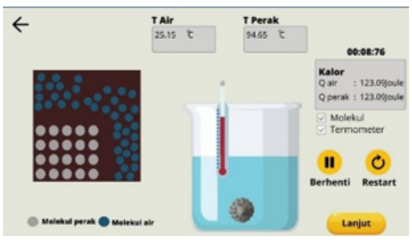

Figure 5. Calorimetry virtual experiment

Figure 6. Heat transfer virtual experiment

Figure 7. Expansion virtual experiment

Figure 8. Experiment data analysis

The virtual laboratory provides three experiment modules that integrate scientific concepts with the silver craftmaking process. The first experiment illustrates the finishing process of silver using the principle of heat transfer and Black's principle of calorimetry, helping students understand the conservation of energy in thermal interactions. The second experiment simulates the heating of silver granules until melting at around 961°C, demonstrating phase changes caused by heat transfer. The third experiment focuses on thermal expansion, shown through the heating of silver wires during ornament assembly, where the expansion of the material becomes observable. These contextualized experiments allow students to directly link abstract physics concepts with authentic local practices, thereby fostering deeper understanding and engagement.

Feasibility of the Virtual Laboratory

The virtual laboratory also underwent an expert validation process during the develop stage. Five validators (three lecturers and two teachers with master's qualifications) assessed the feasibility of the product using criteria adapted from Lestari et al. (2023), which covered content accuracy, design, language, presentation, graphics, technical quality, and the distinctive characteristics of a science virtual laboratory. The validation results are presented in Table 5.

Table 5. Product Feasibility Assessment Results

No	Aspect	Mean Score	Category
1.	Virtual Laboratory Components	14.6	Very Good
2.	Learning Activities with Virtual Laboratory a. Activity 1	7.2	Very Good
	b. Activity 2	7.4	Very Good
	c. Activity 3	7.4	Very Good
3.	Content Accuracy	9.8	Very Good
4.	Language Appropriateness	3.6	Very Good
5.	Presentation	9.8	Very Good
6.	Graphics	10.2	Very Good
7.	Technical Quality and Usability	6.6	Very Good
8.	Distinctive Features of the Virtual Laboratory	3.6	Very Good
Overall Mean		80.2	Very Good
Percentage		94%	

Based on these results, the product achieved an overall feasibility score of 94% in the "very good" category. This indicates that the developed virtual laboratory integrating Kotagede silver crafts within a scientific approach is feasible for science learning. Several revisions were made to improve the quality of the virtual laboratory. The improvements included adding application credits on the loading page, inserting program identity and scientific approach information, and updating the introduction to better highlight the application's advantages. In addition, a separate "Virtual Lab" menu was created to allow direct access to experiment pages, and a help button was added so students could access instructions during the experiments.

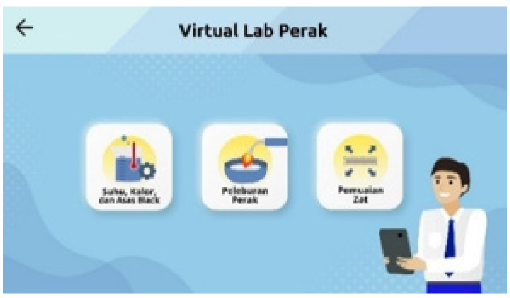

Figure 9. Virtual lab menu

Figure 10. Help button

After being declared feasible by experts, the virtual laboratory and its supporting instruments were further tested for readability. The limited trials revealed that students did not raise significant criticisms, although a few typographical errors needed correction. Operationally, the virtual laboratory ran smoothly, but minor bugs were still encountered during the experiment simulations. These findings indicate that the product was generally acceptable and ready to proceed to practicality testing in classroom settings in the fourth step.

Practicality of the Virtual Laboratory

In educational research, practicality refers to the ease of use, efficiency, and suitability of learning media when applied in real classroom settings. A practical learning medium should not only function technically but also support learning activities without requiring excessive time, cost, or resources (Makransky et al., 2016). In the context of digital media such as virtual laboratories, practicality also relates to whether the application can be smoothly operated by students and teachers, as well as whether it encourages motivation, engagement, and independent learning. Based on Table 6, practicality of the Virtual Lab Perak, as evaluated by students, reached 72.38% with a "good" category.

Table 6. Practicality Assessment Results by Students

Aspect	Mean	(%)	Category
Students' Motivation & Product Attractiveness	5.70	71.25	Good
Ease of Use	11.64	72.75	Good
Benefits of the Product in Developing Critical Thinking Skills	8.70	72.5	Good
Benefits of the Product in Developing Learning Independence	8.76	73	Good
Average		72.375	Good

The aspects assessed included motivation and attractiveness (71.25%), ease of use (72.75%), benefits for critical thinking (72.5%), and benefits for learning independence (73%). These results indicate that students generally perceived the application as helpful and engaging, particularly in supporting independent exploration during virtual experiments. This aligns with research by Lestari et al. (2023), which shows that virtual laboratories can foster student motivation and make abstract science concepts more concrete through interactive simulations. Furthermore, the integration of ethnoscience as the learning context helps students relate scientific concepts to their everyday experiences (Ijatuyi et al., 2025).

Table 7. Practicality Assessment Results by Teachers

Assessment Aspect	Mean	(%)	Category
Content Feasibility	4	100	Very Good
Language	4	100	Very Good
Presentation	3.75	93.75	Very Good
Display	4	100	Very Good
Usefulness	3.75	93.75	Very Good
Average	3.9	97.5	Very Good

From the teachers' perspective, the practicality score was considerably higher, reaching 97.5% with a "very good" category. Teachers rated all aspects highly practical, as presented in Table 7. This suggests that teachers found the Virtual Lab Perak easy to integrate into existing lesson plans and effective in supporting student-centered learning. Teacher validation is crucial, as teachers play a central role in integrating, assessing, and reflecting on the practicality of instructional media in classroom practice (Lawless & Pellegrino, 2007). The difference between students' and teachers' scores indicates that, while teachers recognized the media as highly practical, students rated it lower primarily because they had rarely used virtual laboratories before. As a result, they still required time and experience to adapt to the interface and simulation features. This initial unfamiliarity is common in the introduction of new digital tools and reflects the need for gradual integration and training rather than a lack of practicality. Additional support, such as clearer instructions or brief orientation sessions, could help students become more confident in operating the application. Nevertheless, both perspectives confirm that the Virtual Lab Perak meets the criteria of a practical learning medium. Its implementation demonstrates that digital laboratories can serve as substitutes in contexts where physical facilities are limited (Faulconer & Gruss, 2018).

Effectiveness of the Virtual Laboratory

Results of the field test phase are presented in the form of pretest and post-test analyses to describe students' learning outcomes using the developed virtual laboratory. The recapitulation of students' scores can be seen in Figure 11.

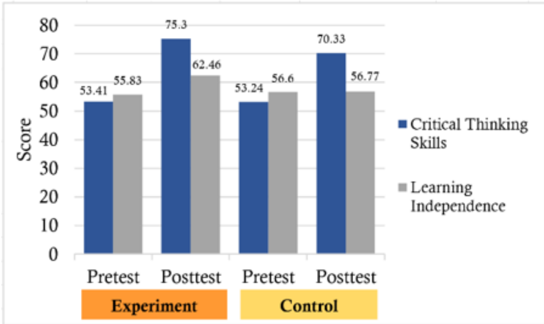

Figure 11. Average pretest and post-test scores of experimental and control classes

At the beginning of the lesson, students were given pretest questions to determine their initial ability. The average pretest scores of both groups were relatively close, showing that the experimental class and the control class began from a comparable starting point. One-way ANOVA confirmed initial equivalence (critical thinking Sig. = 0.941; learning independence Sig. = 0.908, both $\geq$ 0.05), showing no significant pretest difference between groups.

After the learning activities were completed, rosttest results revealed clearer group differences. The experimental class experienced a substantial increase, reaching an average of 75.30 in critical thinking and 62.46 in learning independence. Meanwhile, the control class also showed improvement in critical thinking, rising to 70.33, but learning independence remained nearly unchanged at 56.77.

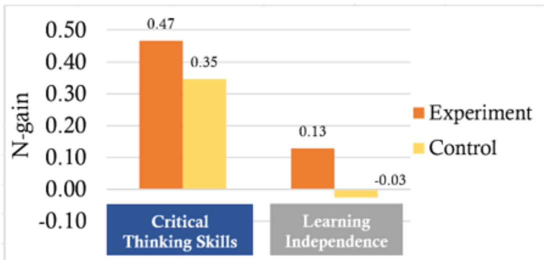

Figure 12. Normalized gain (N-gain) of critical thinking and learning independence

To capture improvement magnitude, normalized gain (N-gain) was calculated (Coletta & Phillips, 2005), as shown in Figure 12. The experimental class reached an N-gain of 0.47 (medium) for critical thinking, exceeding the control's 0.35 (medium-low). For learning independence, the experimental class posted a modest improvement (0.13), whereas the control showed a decline (-0.03). These results confirm that the virtual laboratory is effective in strengthening higher-order thinking and provides at least an initial push toward self-directed learning.

After describing the learning outcomes, the next step was to test the effectiveness of the intervention through multivariate analysis. Before conducting MANOVA, prerequisite tests were carried out to ensure the validity of the analysis based on nine assumptions. First, the data consisted of interval/ratio scale variables and included at least two dependent variables. Measurements were independent, with a sufficient number of subjects, and no outliers were detected ($|Z| \leq 2.5$). Second, normality was satisfied both univariately (Shapiro–Wilk ps > 0.05) and multivariately (Mahalanobis x^2, Sig. > 0.05). Third, the relationship between dependent variables was linear, confirmed by the Deviation from Linearity test (ps > 0.05). Fourth, homogeneity was fulfilled as shown by Levene's test (ps > 0.05) and Box's M test (Sig. = 0.395 > 0.05). Finally, multicollinearity was not present, as tolerance values exceeded 0.1 and VIF values were below 10. These results indicate that all statistical prerequisites were satisfied, ensuring the dataset was valid for MANOVA analysis.

MANOVA is a statistical test designed to examine whether there are significant differences between groups when two or more dependent variables are considered simultaneously (Warne, 2014). In this study, MANOVA was applied to determine whether the use of the virtual laboratory produced greater improvements in critical thinking skills and learning independence compared to conventional instruction. To guide the analysis, three main hypotheses were formulated. Hypothesis 1 tested whether there were simultaneous differences between experimental and control groups across both dependent variables. Hypothesis 2 examined the outcomes separately (univariate) to see whether critical thinking and learning independence were affected differently. Hypothesis 3 compared the mean differences between pretest and posttest scores within each group to determine whether there was a significant improvement over time. Results of the multivariate tests are presented in Table 8.

Table 8. Results of Multivariate Test of Within-Subjects Effects

Source		Value	F	Sig.
Time (pretest-posttest)*group	Hotelling's Trace	0.182	5.835	0.005
posttest*group	Hotelling's Trace	0.251	8.019	0.001

For Hypothesis 1, the interaction between time (pretest–posttest) and group showed a significant effect, indicating that score changes over time differed between the experimental and control groups. Similarly, the posttest × group comparison was also significant, confirming that the two groups achieved different outcomes at the posttest stage. Based on Hotelling's Trace at the 0.05 significance level ($\alpha = 0.05$), H0 is accepted if Sig. > α and rejected if Sig. $\leq \alpha$. Since the obtained significance values were below 0.05, H0 was rejected. Therefore, a second test using univariate analysis was required to examine each dependent variable separately (Table 9).

Table 9. Results of Univariate Test of Within-Subjects Effects

Source		Measure	F	Sig.
Time (pretest-posttest)*group	Greenhouse-Geisser	CTS	4.473	0.038
		LI	8.278	0.005
posttest*group	Greenhouse-Geisser	CTS	8.325	0.005
		LI	7.712	0.007

For Hypothesis 2, the time × group interaction was significant for both critical thinking (F = 4.473, p = 0.038) and learning independence (F = 8.278, p = 0.005). At the posttest stage, significant differences between groups were also found (critical thinking F = 8.325, p = 0.005; learning independence F = 7.712, p = 0.007). Using Greenhouse–Geisser ($\alpha = 0.05$), H0 is accepted if Sig. > 0.05 and rejected if Sig. $\leq$ 0.05. Since all significance values were less than 0.05, H_0 was rejected and H_1 was accepted, meaning that the virtual laboratory produced significantly better outcomes in both critical thinking and learning independence compared to the control condition.

Table 10. Result of Pairwise Comparison

Variable	Treatment	(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.
CTS	Experiment	Pre	Post	-21.894*	1.616	0.000
	Control	Pre	Post	-17.096*	1.592	0.000
LI	Experiment	Pre	Post	-6.626*	1.598	0.000
	Control	Pre	Post	-0.171	1.575	0.914

For Hypothesis 3, pairwise comparisons were used to test whether there was a significant increase in the average scores from pretest to posttest in each group (Table 10). Both groups showed significant gains in critical thinking: the experimental class improved by MD = -21.894 ($p < 0.001$), while the control improved by MD = -17.096 ($p < 0.001$). The negative values of mean difference (pretest – posttest) indicate that posttest scores were significantly higher than pretest scores, thereby rejecting H0 and supporting H1. However, for learning independence, only the experimental group demonstrated significant improvement (MD = -6.626, $p < 0.001$), while the control group's change was negligible (MD = -0.171, p = 0.914). This confirms that the positive change in learning independence was specifically attributable to the virtual laboratory intervention, while conventional instruction failed to produce meaningful improvement.

Table 11. Simultaneous Effect Sizes

Treatment	F	Sig.	Partial Eta Squared
Experiment	94.993	0.000	0.748
Control	57.034	0.000	0.641

Effect size analysis provides a clearer picture of the intervention's impact. As shown in Table 11, when both dependent variables were analyzed simultaneously, the experimental class achieved a partial η^2 of 0.748 (74.8%), while the control class reached 0.641 (64.1%). According to Cohen's benchmark ($\eta^2 > 0.14$ = large effect), both values fall into the large category (Lakens, 2013). However, the experimental group's effect was notably stronger, meaning that the virtual laboratory contributed more effectively to overall improvements in critical thinking and learning independence when considered together.

Table 12. Separate Effext Size

Variabel	Treatment	F	Sig.	η^2
CTS	Experiment	183.520	0.000	0.738
	Control	115.284	0.000	0.639
LI	Experiment	17.188	0.000	0.209
	Control	0.012	0.914	0.000

When the outcomes were analyzed separately (Table 12), a more nuanced picture emerged. For critical thinking, the experimental group recorded a partial η^{2}₂ of 0.738 (73.8%) compared to the control's 0.639 (63.9%). Both effects are large, but the experimental group demonstrated a greater contribution, confirming that inquiry-based activities embedded in the virtual laboratory were particularly effective in stimulating higher-order thinking skills. For learning independence, however, the contrast was striking. The experimental group showed a large effect (partial η^2 = 0.209), indicating that the virtual laboratory successfully nurtured aspects of self-regulated learning such as persistence, responsibility, and self-monitoring. In contrast, the control class produced an effect size of 0.000, meaning that conventional learning had no measurable impact on learning independence. This divergence emphasizes that while both approaches can improve critical thinking, only the virtual laboratory fostered the development of independent learning habits.

Taken together, the results highlight that the virtual laboratory was effective both simultaneously (enhancing students' performance across critical thinking and learning independence in combination) and individually (with particularly strong effects on critical thinking and unique effectiveness in promoting learning independence). This dual effectiveness underscores the value of integrating culturally contextualized simulations into science learning, as they not only sharpen cognitive skills but also cultivate self-regulatory dispositions that conventional methods fail to address. Such innovations are particularly relevant in the context of middle school science, where students often face challenges related to motivation, cognitive ability, and limited instructional resources (de Jong et al., 2013; Sholahudin et al., 2024).

Previous studies consistently report that the use of virtual laboratories can enhance students' higher-order thinking by providing authentic and interactive learning experiences. Virtual experiments not only increased students' motivation but also improved their conceptual understanding in science classes (Herga et al., 2014). Virtual labs support the development of critical thinking because learners are encouraged to hypothesize, test, and evaluate evidence within a safe yet realistic environment . More recent evidence from Sujono et al. (2023) shows that virtual laboratory integration in science classes positively influences students' problem-solving and reasoning skills, which aligns with the significant gains in critical thinking reported in this study.

In addition, the role of virtual laboratories in supporting self-regulated learning has also been highlighted in the literature. Toth et al. (2014) demonstrated that interactive simulations allow students to manage their own pace of learning, thereby strengthening autonomy and persistence. This is consistent with the moderate yet meaningful gains in learning independence achieved by the experimental group in this study. Moreover, localized and culturally integrated virtual environments not only improve academic outcomes but also enhance students' sense of relevance and cultural identity (Yangambi, 2025). Thus, the effectiveness of the Virtual Lab Perak lies not only in its cognitive benefits but also in its capacity to merge scientific learning with cultural wisdom, making it both pedagogically and contextually significant.

CONCLUSION

The developed virtual science laboratory integrated with Kotagede silver crafts and employing a scientific approach was found to be 80.2% feasible in the "very good" category, meeting quality standards for virtual laboratories and principles of scientific learning. The product is practical for classroom use, as confirmed by teacher and student questionnaires as well as classroom observations. It is also effective in improving students' critical thinking, particularly in identifying problems, formulating questions and hypotheses, analyzing data, and drawing conclusions. In addition, the virtual laboratory enhances learning independence by fostering active participation, self-confidence, responsibility, time management, and self-control. These findings highlight the importance of integrating local cultural potentials into science learning and suggest that the virtual laboratory can be further applied to other science topics and expanded with additional features.

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