

The Effectiveness of Metasteps-Based Virtual Biodiversity Learning in Improving Students' Critical Thinking Skills

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Abstract: The widespread integration of digital technology into biology education has created a pressing need for learning platforms that simultaneously engage students and cultivate higher-order thinking skills. Despite the growing adoption of virtual environments and discovery-based learning models, empirical evidence examining their combined pedagogical effect on critical thinking within biodiversity topics remains scarce. This study aimed to evaluate the effectiveness of Metasteps-Based Virtual Biodiversity Learning in improving 10th-grade students' critical thinking skills regarding biodiversity threats and conservation efforts. A pre-experimental approach was employed using a one-group pretest-posttest design, involving 36 tenth-grade students at a private high school in Bandung Regency during the 2025/2026 academic year. The primary instrument was a 15-item multiple-choice critical-thinking test developed based on Facione's indicators, encompassing interpretation, analysis, inference, evaluation, explanation, and self-regulation. Data normality was assessed using the Shapiro–Wilk test; because both pretest and posttest scores were non-normally distributed ($p < 0.05$), the Wilcoxon Signed-Rank Test was applied as the inferential statistical procedure. Effect size was calculated using the formula $r = Z$ divided by the square root of N to quantify the practical significance of the intervention. Results revealed a statistically significant improvement in critical thinking skills from pretest to posttest ($Z = -4.729$; $p < 0.001$), with an effect size of 0.78, classified as moderate according to Cohen's criteria. Indicator-level analysis showed gains across all six dimensions, with the largest improvements observed in analysis and explanation (23 percentage points each). These findings indicate that integrating a three-dimensional virtual biodiversity environment with structured stages of discovery learning can yield meaningful gains in students' critical thinking. The study provides practical evidence for the use of immersive virtual platforms as an alternative science-learning strategy aligned with 21st-century educational demands.

Keywords: Critical Thinking; Metasteps; Virtual Biodiversity.

Introduction

The development of educational technology in the 21st century demands learning innovations that not only improve the quality of the learning process but also develop students' higher-order thinking skills. The integration of digital technology into learning has become a crucial strategy for enhancing student engagement and understanding, as emphasized by UNESCO (2022–2025). Similarly, various studies have shown that using digital simulations and virtual reality in science learning can enhance students' conceptual understanding and analytical skills by providing a more contextual and immersive learning experience [1].

In the context of biology learning, particularly in biodiversity, the use of virtual technology is highly relevant because the objects being studied are complex, dynamic, and often cannot be observed directly. Research by Rosdiani et al. shows that virtual reality-based learning on biodiversity can increase student engagement and learning experiences [2]. Furthermore, Perta et al. found that the use of interactive multimedia in a flipped classroom can increase students' motivation to learn and critical thinking skills [2]. These findings indicate that digital technology has great potential in supporting more meaningful biology learning.

On the other hand, discovery learning-based learning models have also proven effective in improving students' critical thinking skills. A meta-analysis by Khairunnisa showed that discovery learning significantly impacts conceptual understanding and reasoning skills [4]. This approach emphasizes the processes of exploration, analysis, and reflection, which align with Facione's critical thinking indicators: interpretation, analysis, inference, evaluation, explanation, and self-regulation [5][6].

While numerous studies have demonstrated the effectiveness of digital technology and discovery learning models separately, research integrating Virtual Biodiversity learning with step-based learning platforms such as Metasteps remains limited. Most previous research has focused on the partial use of technology or learning models, leaving limited research on how integrating the two can simultaneously enhance students' critical thinking skills in biology learning contexts.

Based on this, the novelty of this research lies in integrating Virtual Biodiversity learning with the Metasteps application, which systematically employs discovery-learning syntax in a digital environment. This integration is expected to create a learning experience that is not only interactive and contextual but also structured to train students' critical thinking skills.

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Therefore, this study aims to analyze the effectiveness of Metasteps-based Virtual Biodiversity learning in improving students' critical thinking skills on biodiversity material.

Research Methods

The research design used in this study is pre-experimental quantitative, employing a one-group pretest-posttest design [7]. The design used in this study is shown in Table 1.

Table 1. Desain penelitian one-group pretest-posttest design

| | | |
|----------------|-----------|----------------|
| Pre-test | Treatment | Post-test |
| O ₁ | X | O ₂ |

This study was conducted at a private high school in Bandung Regency in the odd semester of the 2025/2026 academic year. The research subjects were 10th-grade students with a sample size of 36. The learning process used Virtual Reality-based interactive media via the Metasteps application and was conducted over two meetings. After the treatment, students were given a final test (posttest) to measure their learning outcomes.

The main research instrument was a multiple-choice test consisting of 15 questions, developed based on Ennis's critical thinking indicators, covering students' skills in comprehensive analysis, evaluation, and reflection.

The research procedure was carried out in several stages. First, the preparation stage included the development of Metasteps-based Virtual Biodiversity learning tools and test instruments. Second, the pretest stage was conducted to assess students' initial critical-thinking skills. Third, the treatment stage consisted of Metasteps-based Virtual Biodiversity learning, conducted in two sessions. Fourth, the posttest stage was conducted to measure critical thinking skills after the treatment. Fifth, the data collection stage involved collecting the pretest and posttest results, which were then analyzed statistically.

The data analysis used the Wilcoxon test to determine whether there was a significant difference between the pretest and posttest scores. The Wilcoxon test was used because the pretest and posttest data were not normally distributed [8]. Furthermore, an effect size calculation was performed to determine the magnitude of the treatment's influence on students' critical thinking skills [9]. The effect size was calculated using the formula.

$$r = \frac{Z}{\sqrt{N}}$$

with Z as the statistical value of the Wilcoxon test results and N as the number of research samples.

The research hypotheses consisted of the null hypothesis (H0), which was that there was no significant difference in students' critical thinking skills before and after the application of Virtual Reality-based interactive learning media, and the alternative hypothesis (H1), which was that there was a significant difference in students' critical thinking skills before and after the application of Virtual Reality-based interactive learning media [10].

Results and Discussion

Metasteps serves as a three-dimensional (3D) virtual learning environment in which teachers can deploy a range of digital resources on biodiversity, including images, videos, news articles, scientific information, and structured learning materials. Each resource is embedded in a virtual object positioned in 3D space, allowing students to navigate from one object to another while conducting observational activities. During exploration, students can examine the embedded materials at each virtual station and respond to each object via a built-in comment feature. This feature facilitates a structured exchange between teacher and student, allowing learners to record their observations, articulate analytical conclusions, and submit evidence-based responses. Although the current version of Metasteps does not support real-time direct messaging between students, the comment mechanism effectively scaffolds teacher-student discourse and provides a documented record of student reasoning. The virtual environment is designed to be substantially more interactive than conventional instructional media, promoting active exploration and discovery rather than passive reception of information. By situating biodiversity content within an immersive spatial interface, the platform supports contextual observation and encourages cognitive engagement that aligns with discovery learning principles, thereby contributing to the development of critical-thinking competencies. Figure 1 illustrates the learning environment used during the treatment phase.

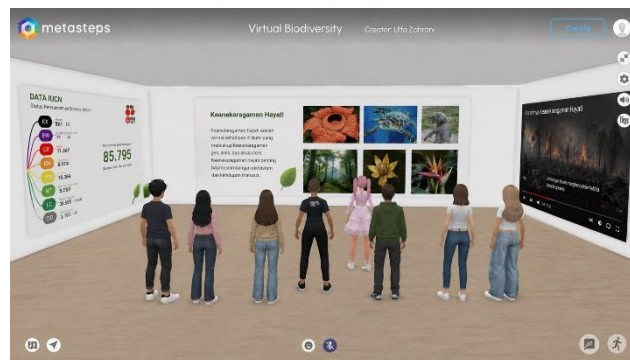


Figure 1. Sample implementation of Metasteps-Based Virtual Biodiversity Learning Environment.

Normality Test

The normality test is a prerequisite test before conducting parametric statistical tests [11]. The normality test was conducted to determine whether the data on students' pretest and posttest critical thinking scores were normally distributed. The following are the results of the normality test of the students' pretest and posttest results:

Table 2. Test of Normality

| | Statistic | Shapiro-Wilk | |
|----------|-----------|--------------|------|
| | | df | Sig. |
| Pretest | .897 | 36 | .003 |
| Posttest | .916 | 36 | .010 |

Based on the Shapiro–Wilk test results, the p-values for the pretest and posttest data are less than 0.05. This

indicates that the data is not normally distributed. This condition indicates that the distribution of student scores deviates from normality, so the use of parametric tests, such as the paired-samples t-test, is not appropriate. Therefore, the analysis was continued with a more appropriate nonparametric test, namely the Wilcoxon Signed-Rank Test.

Wilcoxon Signed-Rank Test

The Wilcoxon test is used to compare pretest and posttest scores in the same group when the data is not normally distributed [12]. The following are the results of the Wilcoxon Signed-Rank Test:

Table 3. Wilcoxon Signed-Rank Test

| | Posttest – Pretest |
|------------------------|---------------------|
| Z | -4.729 ^b |
| Asymp. Sig. (2-tailed) | <.001 |

The analysis results show a Z value of -4.729 with a significance (p-value) < 0.001. A negative Z value indicates that most posttest scores are higher than pretest scores. Meanwhile, the p-value (< 0.001) is less than 0.05, indicating a significant difference between the pretest and posttest scores. This means that the Metasteps-based Virtual Biodiversity learning has a real effect on improving students' critical thinking skills.

Effect Size Test

In addition to statistical significance, it is important to know the extent to which the intervention influences students' critical thinking skills. The Z value obtained is 4.729, and the number of students (N) is 36. The calculation results show an effect size of 0.78. According to Cohen, an effect size value ≥ 0.8 is categorized as large, while a value of around 0.5–0.8 is categorized as moderate [13]. A value of 0.78 indicates that the effect of Metasteps-based Virtual Biodiversity learning on students' critical thinking skills is in the moderate category. This means that the learning intervention is not only statistically significant but also educationally meaningful. An effect size value of 0.78 indicates that Metasteps-based learning can have a substantial impact on critical thinking skills. Students not only experienced an increase in scores but also demonstrated better abilities in analyzing, evaluating, and concluding biodiversity phenomena.

Distribution of Scores per Indicator

To obtain a more in-depth picture, an analysis was also conducted on the distribution of scores for each critical thinking indicator. The analysis showed that all indicators improved from pretest to posttest, with varying degrees of improvement.

The results of the study indicate that Metasteps-based Virtual Biodiversity learning significantly improved students' critical thinking skills. This is demonstrated by the significant difference between pretest and posttest scores (p < 0.001) and an effect size of 0.78, which falls within the moderate-to-large range. These findings indicate that integrating virtual technology with a discovery learning-

based pedagogical approach can create an effective learning environment for developing higher-order thinking skills.

Table 4. Distribution of Critical Thinking Ability Scores per Indicator

| Indicator | Pretest (%) | Posttest (%) | Improvement |
|-----------------|-------------|--------------|-------------|
| Interpretation | 58 | 76 | 18 |
| Analysis | 55 | 78 | 23 |
| Inference | 57 | 74 | 17 |
| Evaluation | 56 | 73 | 17 |
| Explanation | 54 | 77 | 23 |
| Self-Regulation | 52 | 68 | 16 |

Further analysis of the distribution of scores showed that all critical thinking indicators improved: interpretation, analysis, inference, evaluation, explanation, and self-regulation. Variations in the level of improvement between indicators reflect differences in the complexity of the cognitive processes involved in each aspect of critical thinking [6].

The analysis and explanation indicators showed the largest increases, each by 23 points. This increase indicates that Virtual Biodiversity-based learning combined with discovery learning stages is highly effective in training students' ability to process information and construct evidence-based arguments. From a constructivist perspective, the active exploration of phenomena in a virtual environment encourages students to develop an independent, in-depth understanding [14][4].

The interpretation indicator also increased significantly by 18 points. This indicates that the visual and immersive characteristics of Virtual Biodiversity help students understand and identify information more concretely. Visualizing biodiversity phenomena allows students to connect concepts to real-world contexts, thus strengthening the interpretation process [15].

In the inference and evaluation indicators, a relatively balanced increase (17 points) indicates that students are beginning to be able to draw conclusions and evaluate information more critically. This relates to discovery learning-based learning activities that emphasize data collection, information processing, and evidence-based decision-making. Student involvement in the scientific inquiry process has been shown to improve critical thinking skills, particularly in inference and evaluation [16].

Meanwhile, the self-regulation indicator showed the lowest increase, at 16 points. This finding aligns with the characteristics of self-regulation as a metacognitive skill that develops gradually and requires continuous reflective practice [17]. Nevertheless, the improvement indicates that Metasteps-based learning has begun to facilitate the development of students' awareness of thinking.

Conceptually, improvement in each critical thinking indicator is inseparable from the role of the discovery-learning stages integrated into Metasteps. In the stimulus and problem identification stage, students are trained to interpret phenomena and identify problems related to the interpretation and analysis indicators. The data collection and processing stage provides students with opportunities to explore information, compare data, and draw inferences. Furthermore, the verification and generalization stage encourages students to evaluate information, develop

explanations, and reflect on their thinking processes. These stages systematically align with Facione's critical thinking indicators and demonstrate that discovery learning is effective in developing higher-order thinking skills [14][18].

From a technological perspective, the use of Virtual Biodiversity provides an immersive, interactive, and contextual learning experience. Virtual environments allow students to observe complex biodiversity phenomena more realistically, thereby enhancing cognitive engagement and the quality of conceptual understanding. Immersive virtual reality-based learning has also been shown to increase active engagement and learning effectiveness because students are directly involved in exploration and decision-making [19][20].

The integration of Virtual Biodiversity and Metasteps demonstrates that learning effectiveness is determined not only by the use of technology but also by appropriate pedagogical design [21][22]. This approach combines immersive learning experiences with structured scientific thinking processes, thus maximizing the impact on students' critical thinking skills. The effect size of 0.78 indicates that this learning is not only statistically significant but also has practical significance in an educational context. This aligns with findings that learning interventions integrating technology and pedagogy have a greater impact than those using technology alone [23][24].

The implications of this research suggest that Metasteps-based Virtual Biodiversity learning has the potential to be an alternative biology learning strategy that meets the demands of the 21st century. In addition to enhancing critical thinking skills, this approach strengthens students' environmental literacy and ecological awareness. [25][26]. Thus, this learning not only contributes to improved learning outcomes but also to the development of critical-thinking competencies, which are essential in science education.

Conclusion

Metasteps-based Virtual Biodiversity Learning has been shown to positively impact students' critical thinking skills, as evidenced by a significant difference between pretest and posttest scores (effect size = 0.78), placing it in the moderate category. These findings confirm that students not only acquire factual knowledge about threats to and efforts to preserve biodiversity, but also experience real development in their ability to interpret, analyze, draw inferences, evaluate, explain, and engage in self-reflection according to Facione's critical thinking indicators. This effectiveness shows that the integration of Virtual Biodiversity with the Metasteps learning stages can be an alternative science learning strategy relevant to the digital era, as it is able to organize interactive learning processes through discovery learning syntax, thereby creating a contextual, reflective learning experience in line with constructivism theory. Therefore, this innovation is worth considering as an adaptive approach to science learning that meets the demands of the 21st century.

Author's Contribution

N. Faridah and U. Zahrani: conducted the research, performed data analysis, and wrote the manuscript. B. Supriatno and Y. Hamdiyati: as a supervisor, providing

direction and ideas to produce research with interesting ideas.

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