



Enhancing Elementary Students' Conceptual Understanding of Ecosystems through a Metaverse-Based Project-Based Learning Model: A Quasi-Experimental Study

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ABSTRACT

The background of this study is the low conceptual understanding of elementary school students in the Natural and Social Sciences subject, particularly on ecosystem topics, due to conventional and non-technology-based instructional practices. This study aims to analyze the effectiveness of a metaverse-based Project-Based Learning (PjBL) model on elementary students' conceptual understanding. The research employed a quantitative approach with a quasi-experimental methodology using a time series design. The sample consisted of fifth-grade students in Banten, Indonesia. Data were collected using a testing technique with a conceptual understanding test instrument. Data analysis techniques included a one-sample t-test, one-sample binomial test, N-gain test, and paired-sample t-test. The results of the study indicate that: (1) there was an improvement of 25.40 points in students' conceptual understanding after being taught using the metaverse-based PjBL model; (2) the classical mastery level of students' conceptual understanding reached 76.67%; (3) there was a moderate level of improvement in conceptual understanding of 63.33%; and (4) there was a significant difference in students' conceptual understanding before learning, with an average score of 58.30, and after learning, with an average score of 83.70. In conclusion, the metaverse-based PjBL model is effective in improving elementary school students' conceptual understanding of ecosystem topics in the Natural and Social Sciences subject. This study extends previous research on immersive, project-based digital learning at the elementary education level.

Keywords: PjBL; metaverse; elementary; natural and social science; ecosystem

ABSTRAK

Latar belakang penelitian ini adalah rendahnya pemahaman konsep siswa sekolah dasar mata pelajaran mata pelajaran Ilmu Pengetahuan Alam dan Sosial materi Ekosistem karena pembelajaran masih konvensional dan tidak berbasis teknologi. Penelitian ini bertujuan untuk menganalisis keefektifan model PjBL berbasis metaverse terhadap pemahaman konsep siswa sekolah dasar. Penelitian ini menggunakan pendekatan kuantitatif dan metodologi *quasi experimental* dengan *times series design*. Sampel penelitian adalah siswa kelas V di Banten, Indonesia. Teknik pengumpulan data dalam penelitian ini menggunakan teknik tes dengan instrumen tes pemahaman konsep. Teknik analisis data menggunakan uji-t satu sampel, uji binomial satu sampel, uji-N gain, dan uji paired sample t-test. Hasil penelitian meliputi: (1) terdapat peningkatan pemahaman konseptual siswa setelah diajarkan dengan model PjBL berbasis metaverse sebesar 25,40; (2) ketercapaian ketuntasan klasikal pemahaman konseptual siswa adalah 76,67%; (3) terdapat peningkatan pemahaman konseptual siswa dengan kriteria peningkatan sedang sebesar 63,33%, (4) terdapat perbedaan signifikan pemahaman konseptual siswa sebelum belajar dengan rata-rata 58,30 dan setelah belajar dengan rata-rata 83,70. Kesimpulannya model PjBL berbasis metaverse efektif meningkatkan pemahaman konseptual siswa sekolah dasar pada Ilmu Pengetahuan Alam dan Sosial materi Ekosistem. Penelitian ini memperluas penelitian sebelumnya tentang pembelajaran digital berbentuk immersif berbasis proyek di tingkat pendidikan dasar.

Kata Kunci: PjBL; metaverse; sekolah dasar; ilmu pengetahuan alam dan sosial; ekosistem

INTRODUCTION

The rapid advancement of digital technology has reshaped many sectors, including elementary education, creating new opportunities for immersive and interactive learning (Spiteri et al., 2020). One such technological innovation is the metaverse, a three-dimensional, immersive virtual environment that enables users to engage in interactive experiences that bridge the physical and digital worlds (Tsz & Ng, 2022). Metaverse environments have the potential to enhance the quality of learning by facilitating student engagement, collaboration, and contextual understanding beyond traditional educational approaches (Chen et al., 2023).

At the same time, PjBL has been widely recognized as an effective instructional model that emphasizes student-centered inquiry and real-world problem solving (Id et al., 2021). Previous studies demonstrate that PjBL can improve students' science process skills, creativity, and conceptual understanding, especially in elementary school settings (Krajcik et al., 2023). However, the integration of metaverse technology specifically into PjBL strategies for Natural and Social Sciences at the elementary school level remains underexplored. Existing research on metaverse in education has largely focused on general engagement and usability, teacher perceptions, or technology penetration rather than structured pedagogical models like PjBL in specific subject contexts (Fadhli et al., 2023). The implementation of an integrated Project-Based Learning (PjBL) model assisted by the Talking Stick has also been proven to enhance elementary school students' creative and critical thinking skills (Suryaningsih, 2024).

This gap becomes particularly salient in the context of ecosystem learning, where abstract concepts such as biotic-abiotic interactions, food webs, and environmental balance are challenging for young learners to conceptualize through conventional methods alone (Södervik & Nousiainen, 2021). While studies on metaverse in education have highlighted its potential to create immersive experiences (Buragohain et al., 2023). There is limited empirical evidence on how a metaverse-based PjBL model can be designed and implemented to support ecosystem learning in elementary science and social studies concurrently (Rospigliosi, 2022).

Recent studies emphasize that the use of metaverse technology can enhance the quality of learning experiences through immersive, interactive environments that foster meaningful student engagement and collaboration, surpassing conventional learning methods (Zhang et al., 2022). A systematic literature review on metaverse applications in education, highlighted that this technology expands learning opportunities through interactive 3D simulations, enabling exploration of concepts that are often difficult to convey using traditional media, although empirical studies remain limited to specific pedagogical scenarios (Flores-Castañeda et al., 2024). These findings support the argument that integrating metaverse technology with structured pedagogical models such as PjBL holds significant promise for enhancing student engagement, motivation, and learning outcomes in elementary education, particularly in subjects requiring conceptual understanding and collaborative skills, such as Natural and Social Sciences (Zhang et al., 2025).

The novelty of the present study lies in its systematic application of a metaverse-based PjBL model specifically tailored to the integrated Natural and Social Sciences curriculum for fourth grade students, with a focus on ecosystem concepts. Unlike prior research that primarily evaluated general metaverse usage or teacher perspectives, this study empirically examines both implementation and educational outcomes of combining immersive virtual environments with structured project-based pedagogy. Furthermore, it addresses whether this integrated approach can improve student engagement, conceptual understanding, and collaborative skills key objectives in contemporary elementary education.

This study is grounded in constructivist theory pioneered by Jean Piaget and Lev Vygotsky, as well as David A. Kolb's experiential learning theory, which emphasizes that knowledge is actively constructed through direct experience, social interaction, and reflection. In the context of metaverse-based Project-Based Learning (PjBL), immersive virtual environments enable students to experience ecosystem simulations contextually, engage in exploration, collaboration, and authentic problem-solving, thereby facilitating meaningful processes of assimilation and accommodation of concepts. Through the cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation, students' conceptual understanding develops more deeply, as they do not merely receive information but actively construct their own knowledge through interactive, project-based learning experiences (Zunic et al., 2025) .

Therefore, this study aims to implement and evaluate the effectiveness of a metaverse-based PjBL model in teaching Natural and Social Science ecosystem content to fourth-grade elementary school students. Specifically, the objectives of this research are: (1) to examine the extent to which students' average conceptual understanding is achieved after the implementation of the metaverse-based PjBL model; (2) to determine whether students' conceptual understanding reaches the minimum classical mastery criterion of 70% following the use of the metaverse-based PjBL model; (3) to investigate the potential of the metaverse-based PjBL model in enhancing students' conceptual understanding; and (4) to analyze the differences in students' conceptual understanding before and after instruction using the metaverse-based PjBL model. By doing so, the research both supports and extends existing literature on educational metaverse applications and PjBL strategies, offering new insights into how immersive technologies can be pedagogically aligned with student-centered learning objectives in foundational science education. This study contributes to the literature by

empirically examining a metaverse-based PjBL model within integrated elementary Natural and Social Sciences, an area that remains underexplored.

METHODS

Type and Design

This study employed a quantitative approach, which emphasizes the collection and processing of numerical data to address the research questions and objectively test hypotheses. The quantitative approach relies on systematic measurement procedures using standardized instruments, such as tests, surveys, and experiments, which are subsequently analyzed using statistical techniques. The results obtained from this approach are expected to provide rational, measurable, and generalizable conclusions applicable to a broader population.

The research method applied was a quasi-experimental method. A quasi-experimental design is a research framework used to examine the effect of a treatment on the object under study in situations where full randomization is not entirely feasible. The research design used was a time series design, which involves only a single group without a comparison group. In this design, measurements are conducted repeatedly before and after the treatment to observe changes resulting from the learning intervention. Initial measurements are conducted several times as pretests to determine students' baseline conditions, followed by the implementation of the treatment, and concluded with several posttest to identify the impact of the given treatment.

The use of a true experimental design was not feasible in this study due to administrative and ethical constraints in the school setting, which did not allow random assignment of students into experimental and control groups. Nevertheless, a design without a control group remains adequate in this context because it enables the measurement of students' conceptual understanding before and after the intervention within the same cohort, thereby providing valid evidence of learning gains attributable to the implementation of the metaverse-based PjBL model in an authentic classroom environment.

| Sampel | Pretest | Treatment | Posttest |
|--------|---|-----------|---|
| CS | O ₁ O ₂ O ₃ O ₄ | X | O ₅ O ₆ O ₇ O ₈ |

Figure 1. Time Series Design

Description:

| | |
|---|--|
| CS | = Cluster Sampling |
| O ₁ , O ₂ , O ₃ , O ₄ | = Conditions prior to the implementation of the metaverse-based PjBL model, measured through a pretest |
| X | = Implementation of the metaverse-based PjBL model as the treatment |
| O ₅ , O ₆ , O ₇ , O ₈ | = Conditions after the implementation of the metaverse-based PjBL model, measured through a posttest |

Data and Data Sources

The population in this study consisted of all students of the public elementary school SDN Cilenggang 02. The research sample was drawn from Grade VA students of SDN

Cilenggang 02, located in Serpong District, South Tangerang City, Banten. The total number of participants in this study was 30 students ($N = 30$), consisting of 13 male students (43.33%) and 17 female students (56.67%). The participants were elementary school students enrolled in the Natural and Social Sciences subject, with an average age of approximately 10–11 years, representing a typical upper-grade elementary classroom demographic. The sampling technique used was cluster sampling by randomly selecting one class from several available classes, without random assignment into experimental and control groups because the study employed a single-group design. The variables examined in this study included the metaverse-based PjBL model and students' understanding of science concepts related to ecosystem topics. The implementation of this instructional model and media was intended to support students in developing accurate conceptual understanding and to reduce misconceptions through more realistic visual representations and simulations.

Data collection technique

The data collection technique used in this study was a testing method. The test was employed as a measurement tool to determine students' level of conceptual mastery of ecosystem topics. The instrument initially consisted of 40 multiple-choice items and was developed based on indicators of conceptual understanding. Prior to its implementation in the main study, the instrument was piloted with sixth-grade students to examine content validity and empirical validity. Content validity was evaluated by two experts in science education to ensure alignment between the items and learning indicators, while empirical validity was analyzed using item-total correlation. Items with a correlation coefficient (r) greater than the critical r -table value at the 0.05 significance level were considered valid. Reliability was measured using Cronbach's Alpha, yielding a coefficient of $\alpha = 0.87$, which indicates high reliability. Item analysis also included difficulty index and discriminating power. Items were accepted if they met the following criteria: difficulty index ranging from 0.30 to 0.70 (moderate category) and discriminating power ≥ 0.30 (good category). Based on the analysis, 30 out of 40 items met all criteria and were deemed appropriate for use in the study.

The research was conducted over four weeks, consisting of six instructional meetings. The implementation of the metaverse-based Project-Based Learning (PjBL) model followed several stages: (1) problem orientation through ecosystem-related issues presented in the metaverse environment, (2) project planning and group organization, (3) investigation and exploration within the virtual ecosystem simulation, (4) collaborative project development, (5) presentation of project outcomes, and (6) reflection and evaluation. The teacher acted as a facilitator and learning guide, providing scaffolding, monitoring student progress, and supporting technological use, while students actively engaged in exploration, collaboration, discussion, and project creation within the immersive virtual environment.

The metaverse platform used in this study was an immersive virtual learning environment that enabled avatar-based interaction, real-time collaboration, 3D ecosystem simulation, and digital project presentation, thereby supporting contextual and experiential learning processes. In addition to the metaverse-based learning environment, educational videos were used to provide initial conceptual reinforcement and contextual visualization of ecosystem topics, while the Wayground application was utilized as a digital assessment tool to administer quizzes and monitor students' learning progress. Other supporting digital

media, such as interactive presentation slides and online collaboration tools, were also employed to facilitate discussion, project development, and formative feedback during the implementation of the metaverse-based PjBL model.

Data analysis

Data analysis in this study was conducted using inferential statistical techniques. The level of students' conceptual understanding achievement was analyzed using a one-sample t-test, while classical mastery was determined using a one-sample binomial test. The improvement in students' conceptual understanding before and after the treatment was analyzed using the N-gain test. In addition, to examine differences in students' conceptual understanding before and after learning with the metaverse-based PjBL model, a paired-sample t-test was employed. All data analyses were carried out using the predetermined level of significance ($\alpha = 0.05$), and prior to hypothesis testing, prerequisite tests including normality and homogeneity tests were conducted to ensure that the data met the assumptions required for parametric statistical analysis.

RESULTS AND DISCUSSION

1. Implementation of a Metaverse-Based PjBL Model in Elementary School Integrated Science and Social Studies Learning

The implementation of metaverse-based PjBL model in elementary school science and social studies instruction on the topic of ecosystems is designed as a blended learning approach that integrates immersive virtual experiences with tangible, real-world products. The main objectives are to (1) strengthen students' conceptual understanding of components and interactions within various ecosystems (marine, desert, forest, and river), (2) develop scientific skills such as observation and collaboration, and (3) provide authentic learning experiences that motivate students through avatars and virtual environments representing real ecosystem conditions. This approach leverages metaverse features such as 3D exploration, simulations of organism interactions, and virtual presentation spaces to enrich the investigation and project presentation phases, while the creation of physical miniatures bridges virtual learning with children's manipulative skills (Felice et al., 2023).

The implementation followed the stages of metaverse-based PjBL model: (1) **Planning and preparation**, in which the teacher formulated competencies and indicators, prepared assessment rubrics, and selected a child-friendly metaverse platform based on augmented reality; (2) **Orientation and exploration**, where students entered a virtual environment to observe four types of ecosystems through a guided tour, recorded biotic and abiotic components, and identified interesting problems or phenomena as the focus of the project; (3) **Project design**, in which student groups planned a miniature model (including sketches, a list of materials, and member roles) as well as the simulation scenarios to be tested; (4) **Construction and data collection**, where groups built physical miniatures (marine, desert, forest, and river ecosystems) at school or at home while using the virtual space to test hypotheses, simulate changes, and record observation results; (5) **Testing, presentation, and reflection**, in which each group synchronously presented their

work in the classroom through a project exhibition, received peer feedback, and conducted structured reflection; and (6) **Assessment and documentation**, where the teacher evaluated both the product and the process using rubrics that assessed conceptual understanding, practical skills, collaboration, and digital literacy, and archived the project artifacts. The steps of the pJBL model can enhance collaborative, interactive, and authentic learning, as well as produce student engagement (Almulla, 2020). The PjBL model can be categorized as a learning model that can improve student learning outcomes in science and train students in problem-solving & critical thinking (Chistyakov et al., 2023).

The final products produced were scale models of marine, desert, forest, and river ecosystems, accompanied by a brief scientific report, process documentation (photos/videos), and demonstrations illustrating the functions of ecosystem components and their responses to environmental changes. The assessment employed a holistic rubric integrating conceptual understanding (short tests/quizzes or reflective questions), practical skills (creativity in constructing the models and accuracy of representation), critical thinking skills (analysis of the impacts of environmental changes), and digital collaboration (contributions within the metaverse environment). Recent research and reviews indicate that integrating the metaverse into a PjBL curriculum can enhance students' motivation and engagement, provided that it is supported by well-designed pedagogy and adequate access to technology (Rachmadtullah, 2023; Wang, 2025).

2. Average Achievement of Science Concept Understanding in Elementary School Students After Using the Metaverse-Based PjBL Learning Model

To assess the average level of students' understanding of science concepts in elementary schools after the implementation of the Metaverse-based PjBL model, data analysis can be conducted using hypothesis testing with a one-sample t-test. However, before performing the hypothesis test, the data must first meet statistical requirements, specifically through a normality test to ensure that the data distribution is normal. Therefore, a prerequisite test in the form of a normality test was conducted on the students' science concept understanding data as a basis for the feasibility of further analysis.

Table 1. Normality test results

| | Kolmogorov-Sminrov | | |
|----------|--------------------|----|-------|
| | Statistic | df | Sig |
| Pretest | 0,156 | 30 | 0,200 |
| Posttest | 0,247 | 30 | 0,141 |

Based on the results of the normality test presented in Table 1, the significance value of the pretest data was 0,200, and the posttest data was 0,141. Both values exceed the significance threshold of 0,05, so the null hypothesis (H_0) is accepted. This indicates that the research data are normally distributed and meet the prerequisites for further testing. Therefore, the analysis can proceed using a one-sample t-test. Subsequently, the one-sample t-test was applied to measure the level of achievement in understanding Science and Social Studies concepts among elementary school students following the implementation of the metaverse-based PjBL model. The following graph illustrates the

improvement in students' conceptual understanding after the implementation of the metaverse-based PjBL model, as shown in Figure 1.

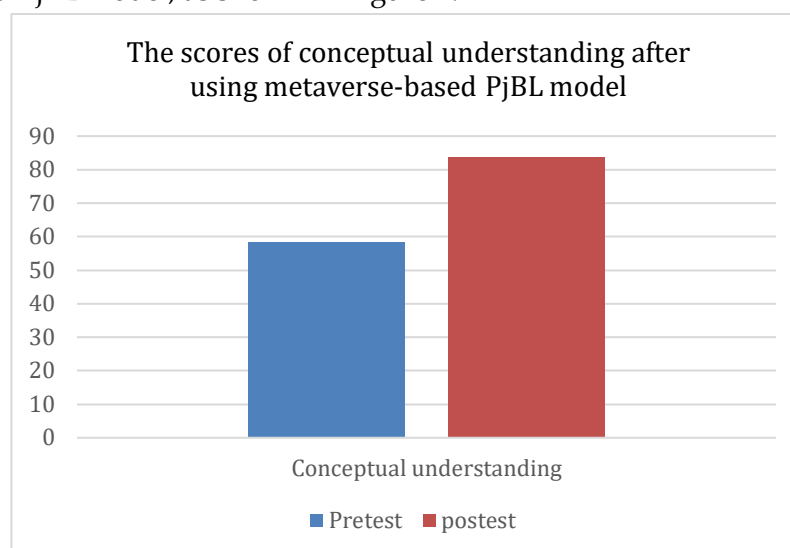


Figure 1. The results of students' pretest and posttest scores on conceptual understanding after the implementation of the metaverse-based PjBL model

Based on Figure 1, it is known that the average student conceptual understanding before implementing the metaverse-based PjBL model was 58.30. After the learning process was conducted using the metaverse-based PjBL model, the average student conceptual understanding increased to 83,70. This difference in average scores indicates an improvement of 25,40 points in students' conceptual understanding following the implementation of the PjBL model assisted by metaverse media.

Table 2. One sample t-test output results

| Test Value = 70 | | | | | | |
|-----------------|-------|----|----------------|-----------------|---|-------|
| | T | df | Sig (2-tailed) | Mean difference | 95% confidence interval of the difference | |
| | | | | | lower | Upper |
| Pretest | 2,214 | 30 | 0,000 | 6,676 | -13,08 | -4,31 |
| Posttest | 3,675 | 30 | 0,001 | 6,214 | 2,84 | 9,77 |

The results of the one-sample test presented in Table 3 show a significance value of 0,01, which is below the 0,05 threshold. Consequently, the alternative hypothesis (H_1) is accepted. These results indicate that the students' average conceptual understanding after learning through the metaverse-based PjBL model differs from the KKM benchmark of 70, achieving an average score of 83,70.

3. Students' Conceptual Understanding Achievement Following Metaverse-Based PjBL Implementation

To assess the extent to which classical mastery in students' conceptual understanding was achieved following the implementation of the metaverse-based PjBL model, statistical analysis was conducted using the one-sample binomial test. The results of the one-sample binomial test concerning the level of classical mastery are subsequently presented in detail in Table 3.

Table 3. One sample binomial test output results

| | Category | N | Observed Prop. | Test Prop. | Exact Sig (2-tailed) |
|--------------------------|----------|-------|----------------|------------|----------------------|
| conceptual understanding | Group 1 | <= 70 | 7 | 0,23 | 0,50 |
| | Group 2 | > 70 | 23 | 0,77 | 0,11 |
| | Total | | 30 | 1,00 | |

Based on the results of the binomial test presented in Table 4, it was found that 77% of the students (23 out of 30) achieved scores above 70, while the remaining 23% of students (7 out of 30) scored at or below 70. These findings indicate that the implementation of the metaverse-based PjBL model was able to achieve a classical mastery level of students' conceptual understanding of 77%. Further details on the attainment of individual and classical learning mastery in the experimental class are presented Table 4.

Table 4 Classical Completion of Experimental Class

| | Before treatment | After treatment |
|------------------------------------|------------------|-----------------|
| Number of students completed | 13 | 23 |
| Number of students not completed | 17 | 7 |
| Average value | 58,30 | 83,70 |
| Percentage of classical completion | 43,33% | 76,67% |
| Category | Incompleted | Completed |

Based on the data presented in Table 5 regarding classical completeness in the experimental class, it can be observed that students' conceptual understanding was still relatively low prior to the implementation of the metaverse-based PjBL model. The initial average score was 58,30, with a classical completeness percentage of only 43,33%, categorizing it as incomplete. However, following the implementation of the model, a significant improvement in students' learning outcomes was observed, indicated by an increase in the average score to 83,70 and a classical completeness percentage of 76,67%, thereby meeting the completeness criteria.

4. Enhancing Students' Conceptual Understanding through the Implementation of a Metaverse-Based PjBL Learning Model

To evaluate the effectiveness of the metaverse-based PjBL model in enhancing students' conceptual understanding, an analysis was conducted using the N-gain test. The N-gain results, reflecting the level of improvement in conceptual understanding in Science and Social Studies among elementary school students, are presented in detail in Table 5.

Table 5. N-Gain test results

| Score | Criteria | Total | Percentage (%) |
|-----------------------------|----------|-------|----------------|
| N-gain $\geq 0,70$ | High | 4 | 13,33% |
| $0,30 \leq$ N-gain $< 0,70$ | Medium | 19 | 63,33% |
| N-gain $< 0,30$ | Low | 7 | 23,33% |
| Total | | 30 | 100% |

5. Changes in Students' Conceptual Understanding Before and After the Implementation of a metaverse-based PjBL learning model

To examine whether there is a significant difference in students' conceptual understanding before and after the implementation of the metaverse-based PjBL model, the analysis was conducted using a paired sample t-test. Prior to performing the hypothesis test, a prerequisite test, namely the normality test, was conducted to ensure that the data followed a normal distribution. The results of the normality test for students' conceptual understanding scores before and after the implementation of the metaverse-based PjBL model are presented in Table 1. Since the data were confirmed to be normally distributed, the analysis proceeded with the paired sample t-test, the results of which are presented in the following table.

Table 6. output *paired samples test*

| | Paired Differences | | | 95% interval of the difference | t | df | Sig (2- tailed) | |
|------------------------------|--------------------|-------------------|-----------------------|---|---------|--------|-----------------------|-------|
| | Mean | Std. Deviation | Std. Error Mean | | | | | lower |
| Pair Pretest- Posttest | -15,000 | 5,000 | 1,043 | -17,162 | -12,838 | 14,387 | 22 | 0,000 |

Based on Table 8 in the Paired Samples Test presents a significance value (sig. 2-tailed) of 0.000, which is below the 0.05 threshold. This result indicates that the alternative hypothesis (H_1) is accepted, meaning there is a significant difference in students' conceptual understanding before and after implementing the metaverse-based PjBL model, with the mean score increasing from 58,30 to 83,70.

Based on the results of the paired-sample t-test, the effect size was calculated using the Cohen's d formula for paired samples. With a t value of 14.387 and $N = 23$ ($df = 22$), the obtained Cohen's d value was 2.99, which falls into the category of a very large effect size. This indicates that the implementation of the metaverse-based PjBL model was not only statistically significant but also had a very strong practical impact on improving students' conceptual understanding.

DISCUSSION

Based on the research findings, it was found that the implementation of the metaverse-based Project-Based Learning (PjBL) model significantly improved elementary school students' conceptual understanding of ecosystem topics. The average student score increased from 58.30 before the intervention to 83.70 after the implementation, with a gain of 25.40 points. In addition, classical mastery improved from 43.33% (incomplete category) to 76.67%, indicating that most students achieved the predetermined mastery criteria after participating in the metaverse-assisted learning process. Statistical analysis further strengthened these findings, as the paired-sample t-test showed a significance value below 0.05, indicating a significant difference between pretest and posttest scores. Moreover, the effect size (Cohen's $d = 2.99$) was categorized as a very large effect, suggesting that the metaverse-based PjBL model not only produced statistically significant differences but also had a very strong practical

impact on improving students' conceptual understanding in Natural and Social Sciences learning.

These findings align with constructivist theory, which posits that students actively construct knowledge through meaningful experiences, social interaction, and problem-solving processes embedded in authentic contexts. Furthermore, from the perspective of experiential learning theory, the metaverse-based PjBL model facilitates concrete experiences, reflective observation, abstract conceptualization, and active experimentation, thereby promoting deeper conceptual understanding through immersive and project-driven learning activities. The implementation of a metaverse-based PjBL model in teaching Natural and Social Sciences on the topic of ecosystems in elementary schools exhibits substantial potential to enhance students' conceptual understanding. The Metaverse provides an immersive virtual learning environment, enabling students to engage in authentic and contextually rich learning experiences. Within this virtual space, students can interact with three-dimensional ecosystem simulations, facilitating a visual and participatory comprehension of the interrelationships between biotic and abiotic components (Said, 2023). The integration of the PjBL model with Metaverse technology promotes active engagement, collaboration, and higher-order thinking skills, thereby deepening students' grasp of abstract concepts through experiential learning and autonomous exploration in digital projects (Shu & Gu, 2023). This is in line with the Lapbook-based Project-Based Learning (PjBL) model can improve students' mathematics learning outcomes (Nurhabibah, 2023).

Digital media in the form of educational videos functions as a visual aid that can enhance elementary school students' critical thinking skills by encouraging more active, reflective, and in-depth information processing (Hsu et al., 2022). Pedagogically designed videos can map ecological processes, such as food chains or material cycles, with clear and contextualized steps, thereby helping students build accurate mental representations of ecosystem concepts. The combination of educational videos with an immersive metaverse environment allows students not only to observe but also to experience ecosystem dynamics through visual narratives and interactive activities guided by project objectives an approach recognized as effective in enhancing student engagement and academic achievement in the digital era (Chang et al., 2022).

Furthermore, Augmented Reality (AR) media has become an important element in science and social studies learning due to its ability to present three-dimensional objects or phenomena in real time within the real world (Scavarelli et al., 2020). Through AR, students can view visual representations of ecosystem components (such as marine organisms, deserts, forests, and rivers) that were previously available only in textual or two-dimensional formats. This 3D visualization enables students to more easily connect theoretical concepts with real-world phenomena around them, thereby accelerating comprehension and strengthening long-term memory of the scientific concepts being learned (Korakakis et al., 2009). The application of augmented reality (AR) to the solar system has received positive responses from both teachers and students because it can actively engage students in science learning (Muhabib, 2025; Riduan & Suryani, 2024).

Within the framework of metaverse-based PjBL model, students do not merely receive information passively but are actively engaged in producing tangible artifacts, namely miniatures of marine ecosystems, desert ecosystems, forest ecosystems, and river ecosystems.

These products require students to apply scientific concepts through stages of planning, development, and reflection on their own findings. This project-centered learning process has been shown to strengthen deep learning, in which students construct transformative understanding of subject matter through authentic and meaningful learning experiences (Sánchez-lópez et al., 2022). The implementation of the PjBL model facilitates students in continuously connecting theoretical knowledge with real-world practice, thereby making conceptual understanding more stable and meaningful in the long term (Aubrey, 2021).

Finally, the use of digital media such as the Wayground application for cognitive assessment plays a role as an adaptive and interactive formative evaluation tool. The use of gamified e-quizzes such as Quizizz as a formative assessment tool has been proven effective in enhancing students' engagement and motivation through competitive features, instant feedback, and game elements, which ultimately have a positive impact on learning performance (Zainuddin et al., 2020). By providing immediate feedback based on individual student performance, this application supports rapid and targeted conceptual improvement before students proceed to the next stage of the project. Such applications integrate assessment with the learning process, so they not only measure learning outcomes but also help students directly address misconceptions within the context of the digital learning activities they engage in (Timmis et al., 2016).

Based on the discussion above, it can be concluded that the metaverse-based PjBL model is effective in improving elementary school students' conceptual understanding of natural and social sciences in ecosystem topics. The use of immersive metaverse learning environments enables students to directly experience and explore ecosystems, thereby making abstract concepts more concrete (Benaben & Fertier, 2025). Augmented Reality (AR)-based digital media in experiment-based learning has a significant impact on enhancing students' attention, material relevance, confidence, and learning satisfaction through immersive and contextual interactive visual experiences (Prasetya et al., 2024). Furthermore, students' involvement in creating ecosystem miniatures supports the practical application of concepts, promotes deep learning, and enhances critical thinking skills. Overall, the integration of PjBL with metaverse technology creates an interactive, authentic, and effective learning experience that strengthens elementary students' mastery of natural and social science concepts.

Despite its positive findings, this study has several limitations that should be acknowledged to enhance academic rigor and transparency. First, the use of a single-group quasi-experimental design without a control group limits the ability to attribute learning gains solely to the metaverse-based PjBL intervention, as external variables may have influenced the results. Second, the relatively small sample size ($N = 30$) drawn from one elementary school restricts the generalizability of the findings to broader educational contexts. Third, the duration of the intervention was limited to several weeks, which may not fully capture long-term retention effects or sustained conceptual change. Therefore, future studies are recommended to employ larger and more diverse samples, include control or comparison groups, and conduct longitudinal investigations to provide more robust evidence regarding the effectiveness of metaverse-based PjBL in elementary science and social studies learning.

CONCLUSION

Based on the findings and discussion, it can be concluded that the metaverse-based Project-Based Learning (PjBL) model significantly enhances elementary school students' conceptual understanding of ecosystem topics in Natural and Social Sciences. The substantial increase in mean scores, improved classical mastery, and very strong practical impact indicate that integrating immersive digital environments with project-based pedagogy can meaningfully strengthen conceptual learning at the primary education level. Beyond improving short-term achievement, this model demonstrates the potential to transform elementary classroom practices by fostering active engagement, contextual exploration, collaboration, and deeper knowledge construction aligned with 21st-century learning demands.

From a broader educational perspective, the findings suggest that metaverse-supported PjBL can serve as an innovative framework for integrating technology into elementary curricula in a pedagogically meaningful way, rather than merely as a supplementary tool. The scalability of this model across different schools and regions highlights its relevance for digital transformation initiatives and education policy aimed at strengthening technology-enhanced learning in primary education. Nevertheless, given the limitations of a single-group design and a relatively small sample, future research should employ more rigorous experimental designs with control groups, larger and more diverse samples, and longitudinal approaches to examine long-term conceptual retention, higher-order thinking development, and sustainable implementation at scale.

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