



Integrated Virtual Reality Learning Framework with Digital Ecosystem for Enhancing Physics Conceptual Understanding

Eko Risdianto¹ , Joseline Santos² , Noel Lomerio² , Deshinta Arrova Dewi³ ,
M. Esad Kuloglu⁴ , Sultan Hammad Alshammari⁵ , Ressti Nurfitriani¹

¹Doctoral Program in Education, Faculty of Teacher Training and Education, Universitas Bengkulu, Bengkulu, Indonesia

²Bachelor of Technology and Livelihood Education, College of Professional Teacher Education, Bulacan State University, Bulacan, Philippines

³ Center for Data Science and Sustainable Technologies, INTI Internasional University, Nilai, Malaysia

⁴School of Foreign Languages, Abdullah Gul University, Kayseri, Turkiye

⁵Department of Educational Technology, College of Education, University of Ha'il, Ha'il, Saudi Arabia

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ABSTRACT

Purpose of the study: This study develops and evaluates an integrated virtual reality learning framework to improve high school students' physics conceptual understanding. The framework combines immersive 360° virtual reality videos via Kuula with Google Classroom, ClassPoint, digital flipbooks, and PhET simulations within a problem-based learning environment.

Methodology: This study employed a research and development approach using the ADDIE model, combined with a pre-experimental one-group pretest–posttest design. The participants consisted of three cohorts of high school students ($n = 115$) across different physics topics: Kinematics ($n = 36$), fluids ($n = 39$), and particle dynamics ($n = 40$). The framework was validated by three experts using structured instruments assessing content, media, language, and presentation aspects. Data were collected through validation sheets, student response questionnaires, and conceptual understanding tests. Data analysis included percentage-based measures, N-Gain, Shapiro Wilk tests, paired t-tests, Wilcoxon signed rank tests, and effect size calculations.

Main Findings: The results indicate high validity (88.89%–97%) and practicality (86%–98%). The implementation was associated with significant improvements in conceptual understanding, reflected in high N-Gain scores (0.81–0.87) and large effect sizes ($p < 0.05$). These findings suggest that the integrated virtual reality based learning ecosystem can effectively support conceptual understanding within the studied context.

Novelty/Originality of this study: The novelty lies in the systematic integration of the Kuula platform within a multi-component digital learning ecosystem under a problem based learning framework, as well as its application across multiple physics topics to demonstrate consistent learning outcomes.

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Corresponding Author:

Eko Risdianto,

Doctoral Program in Education, Universitas Bengkulu,

Jl. W.R. Supratman, Kandang Limun, Muara Bangkahulu, Bengkulu, 38371, Indonesia

Email: eko_risdianto@unib.ac.id

1. INTRODUCTION

The rapid development of digital technology in the Education 4.0 era has brought about significant transformation in learning practices, especially in science education [1]-[3]. Physics learning, which is full of abstract concepts, mathematical representations, and dynamic phenomena, demands learning strategies that are able to encourage deep conceptual understanding, not just procedural mastery or memorizing formulas [4]-[6]. Conceptual understanding in physics includes the ability to interpret, explain, compare, classify, and apply scientific principles in various contexts [7], [8]. However, various studies show that high school students still experience misconceptions in materials such as kinematics, fluids, and particle dynamics due to difficulties in visualizing invisible forces, motion interactions, and pressure and acceleration phenomena [9]. Studies in science education confirm that visualization and interactive representation are important factors in fostering conceptual change [10]. Traditional learning that relies on static diagrams and mathematical symbols is often unable to help students build a complete mental model [11].

The need for more effective visualization strategies has encouraged the adoption of immersive learning technologies. The potential of such technologies can be explained through established cognitive theories, including the cognitive theory of multimedia learning and dual coding theory, which emphasize the integration of visual and verbal representations to support meaningful learning [12], [13]. Among these technologies, virtual reality has emerged as a promising tool for providing immersive and interactive three-dimensional learning environments [14], [15]. Previous studies have demonstrated that virtual reality can enhance student engagement, spatial abilities, knowledge retention, and conceptual understanding when implemented with appropriate instructional design principles [16]-[18]. In physics education, virtual reality enables students to explore abstract phenomena through contextualized and interactive experiences that are difficult to achieve through conventional instruction. Despite these promising findings, several limitations remain in the current body of virtual reality research.

Although virtual reality has been shown to improve student engagement, spatial understanding, and learning outcomes in science education [19], existing studies largely focus on single physics topics and often use virtual reality as a standalone visualization tool [20], [21]. Research examining the integration of virtual reality within a comprehensive digital learning ecosystem and its effectiveness across multiple topics and student cohorts remains limited. Previous studies emphasize that the success of immersive learning depends more on pedagogical design than on technology itself [22]. To address these gaps, this study proposes an integrated virtual reality-based learning framework that combines immersive virtual reality, supporting digital tools, and a structured pedagogical approach. Its novelty lies in three aspects: (1) integrating virtual reality within a multi-component digital learning ecosystem, (2) embedding virtual reality in a problem-based learning environment to ensure pedagogically driven implementation [23], [24], and (3) evaluating the framework across multiple physics topics and student cohorts [25]. Since immersive technologies are most effective when combined with active learning approaches such as problem based learning [26], this framework also incorporates learning management systems, interactive assessments, and simulations to enhance cognitive engagement while reducing extraneous cognitive load. This study therefore contributes a more comprehensive and scalable model for virtual reality-based physics learning at the secondary school level, an area that has received limited systematic investigation [27]. To ensure the pedagogical validity of the proposed framework, its design is grounded in established cognitive and instructional learning theories.

The proposed framework is grounded in the integration of cognitive and pedagogical learning theories that directly inform its design [28]-[30]. Cognitive load theory guides the development of instructional materials that reduce extraneous cognitive load and promote meaningful learning through contextualized 360° virtual reality experiences [31]. The cognitive theory of multimedia learning supports the use of multiple representations, combining immersive virtual reality, digital flipbooks, and PhET simulations to facilitate information processing across visual and verbal channels [32]. Dual coding theory further justifies the integration of visual and symbolic representations, enabling stronger knowledge encoding and retrieval [33]. In addition, the framework is pedagogically structured through problem-based learning [24], which promotes active knowledge construction, collaborative inquiry, and reflective learning. Consequently, virtual reality and supporting digital tools function not as isolated technologies but as components of a coherent instructional design aimed at enhancing conceptual understanding. By aligning cognitive principles with pedagogical strategies, the framework ensures that technology integration is both educationally meaningful and cognitively effective [34].

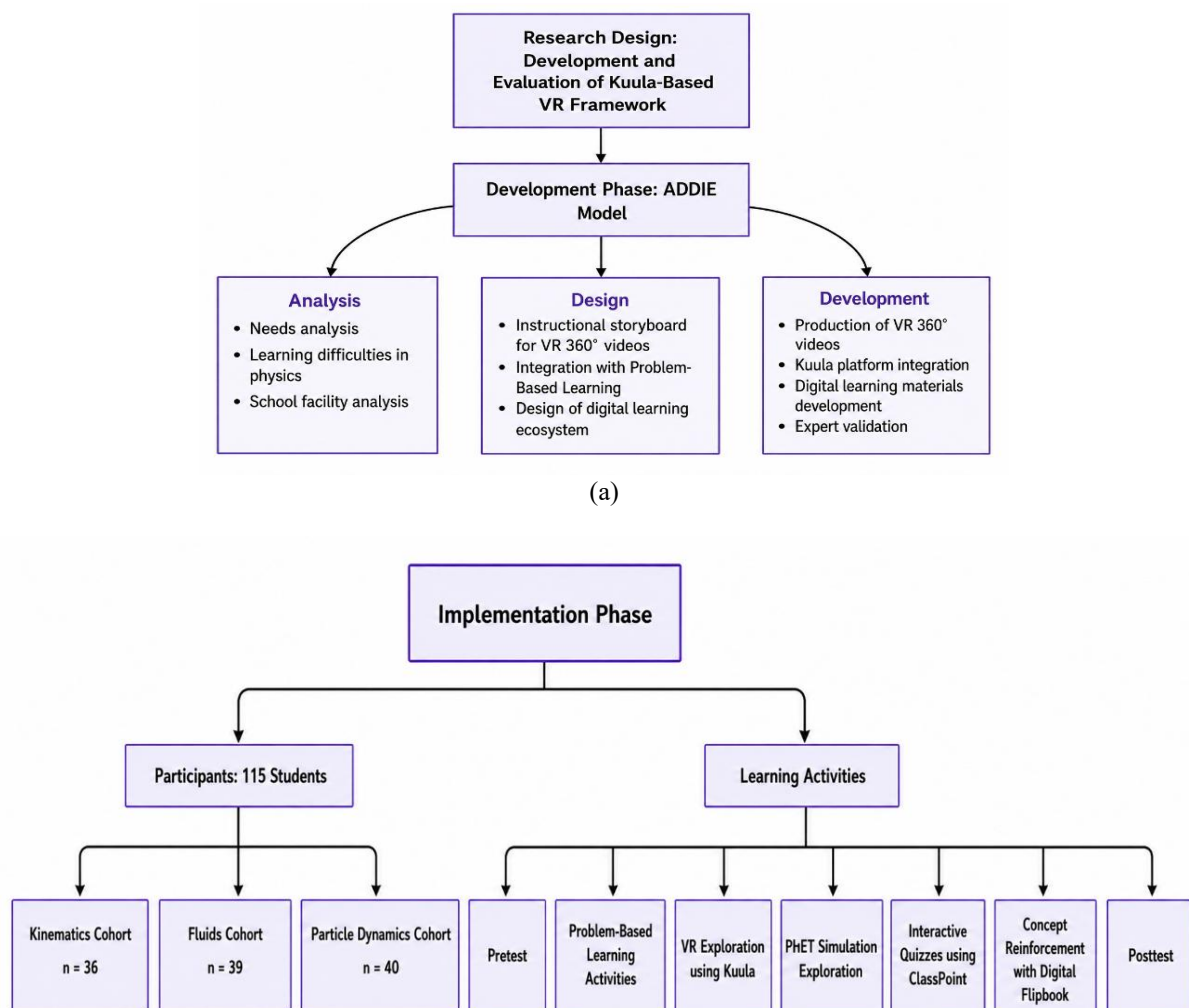
Based on this background, this study develops and evaluates an integrated Kuula-based virtual reality framework for physics learning in high schools [35]. The Kuula platform is used as a web-based 360° virtual reality content presentation medium that can be accessed without expensive devices [36]. Unlike previous research that positioned virtual reality as a single medium, the framework developed in this study integrates virtual reality with Google Classroom as a learning manager, ClassPoint as a means of direct interaction and feedback, digital flipbooks as conceptual reinforcement, and PhET Simulation as a medium for virtual variable exploration. The entire learning design is structured using the ADDIE development model and implemented in a problem-based learning approach to encourage active and meaningful knowledge construction [37]. This framework was

implemented on three different physics topics, namely kinematics ($n = 36$), Fluids ($n = 39$), and particle dynamics ($n = 40$), with a total of 115 high school students. This cross-topic and cross-cohort application provides a broader empirical basis in assessing the consistency and scalability of the developed virtual reality based learning framework [38]. Theoretically, this research is based on Bruner's representation theory, dual coding theory, and cognitive theory of multimedia learning which emphasizes the importance of integrating visual, verbal, and direct experience representations in building conceptual understanding [39], [40]. By combining an immersive virtual reality environment, interactive simulation, and a problem-based approach, this research is expected to contribute to the development of an innovative, validated, and applicable physics learning ecosystem in schools with limited laboratory facilities. Specifically, the objectives of this research are: (1) to develop and validate an integrated Kuula-based virtual reality learning framework; (2) to analyze the practicality of the framework based on student responses; and (3) to evaluate its effectiveness in improving students' conceptual understanding across various physics topics and cohorts.

2. RESEARCH METHOD

2.1. Types and Research Design

This study employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) to develop an integrated kuula-based virtual reality framework for high school physics learning. To evaluate its effectiveness, a one-group pretest–posttest pre-experimental design was embedded within the summative evaluation phase and implemented across three student cohorts. Thus, the study represents developmental research with an embedded pre-experimental evaluation, combining systematic framework development with empirical testing in real classroom settings. However, the absence of a control group, randomization, and controls for potential confounding variables limits causal interpretation. Therefore, the findings should be viewed as evidence of the framework's potential effectiveness rather than definitive proof of causality.



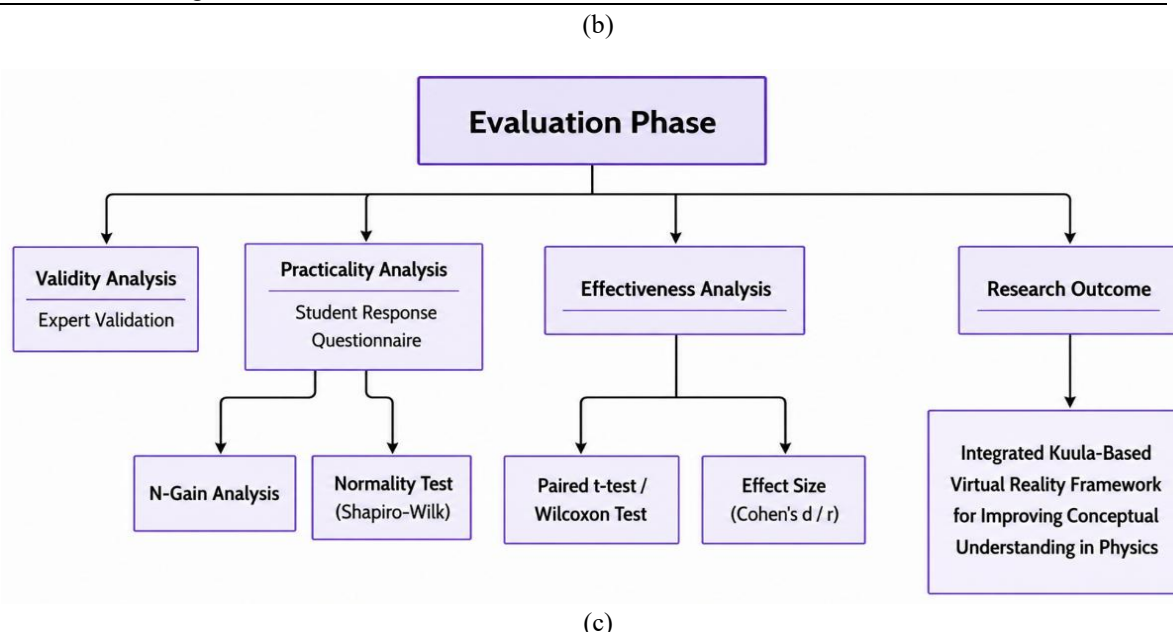


Figure 1. Research design and evaluation framework (a, b, c) for the integrated Kuula-based virtual reality learning environment.

2.2. Research Subjects

The participants in this study consisted of 115 high school students from a single school in Bengkulu City, divided into three cohorts based on grade level and physics topics: 36 tenth-grade students studying Kinematics, 39 eleventh-grade students studying Fluids, and 40 eleventh-grade students studying Particle Dynamics. The multi-cohort design was employed to examine the consistency and effectiveness of the developed Kuula-based Virtual Reality framework across different subject matters. Participants were selected using a convenience sampling technique based on accessibility and the feasibility of implementing the framework within the school context [41], [42]. Although the study was conducted in a single institution, the inclusion of multiple classes enabled cross-topic comparison within an authentic classroom setting. Ethical approval was obtained from the institutional research ethics committee, and informed consent was secured from all participants. While this sampling approach limits generalizability, it allows for practical evaluation of the framework under real educational conditions.

2.3. Development Procedures Using the ADDIE Model

This study employed the ADDIE model, which consists of five systematic stages: analysis, design, development, implementation, and evaluation, to develop the integrated kuula-based virtual reality learning framework. In the analysis stage, a needs assessment was conducted to identify students' conceptual difficulties in physics, learning characteristics, and the technological conditions of the classroom. This stage also involved reviewing relevant literature to ensure alignment with current instructional and technological trends. The design stage focused on structuring the learning framework by integrating immersive 360° virtual reality experiences with supporting digital tools, including Google Classroom, ClassPoint, digital flipbooks, and PhET simulations. The instructional flow was designed based on problem-based learning principles to promote active and inquiry-based learning. During the development stage, learning materials and media were produced, including virtual reality content using the Kuula platform, interactive simulations, and digital learning resources. The developed components were then evaluated by experts to assess content accuracy, instructional quality, media design, and language clarity. The implementation stage involved applying the framework in three student cohorts across different physics topics under authentic classroom conditions. Finally, the evaluation stage included formative evaluation through expert validation and summative evaluation using pretest–posttest data to assess improvements in students' conceptual understanding. This systematic process ensured that the learning framework was pedagogically grounded, technologically integrated, and empirically evaluated.

2.4. Validation Instruments

The validation of the developed learning framework was conducted using a structured expert judgment instrument. The instrument was designed to assess four main aspects: (1) content validity, (2) presentation quality, (3) language clarity, and (4) media design. Each aspect of the validation instrument consisted of several indicators assessed using a four-point Likert scale, where 1 = Not Appropriate, 2 = Less Appropriate, 3 = Appropriate, and 4 = Highly Appropriate. Prior to implementation, the instrument was reviewed to ensure the clarity, relevance, and

comprehensiveness of all indicators. The scores assigned by each validator were then summed and converted into percentage values using the formula: $\text{Percentage} = (\text{Total Score Obtained} / \text{Maximum Possible Score}) \times 100\%$. The overall validity level of the framework was determined by calculating the average percentage across all validation aspects and validators.

2.5. Data Analysis Techniques

Validity and Practicality Analysis

Data was analyzed using percentage scores:

$$\text{Percentage} = \frac{\text{Score obtained}}{\text{Maximum score}} = 100\% \quad \dots(1)$$

Table 1. Interpretation Categories

Percentage (%)	Category
76%–100%	Very Feasible
51%–75%	Feasible
26%–50%	Less Feasible
0%–25%	Not feasible

Effectiveness Analysis

The increase in conceptual understanding was analyzed using the N-Gain formula:

$$\text{Percentage} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum score} - \text{Pretest score}} \quad \dots(2)$$

Table 2. N-Gain Range and Category

N-Gain Range	Category
$g \geq 0.7$	High
$0.3 \leq g < 0.7$	Medium
$g < 0.3$	Low

This Analyses were conducted per cohort and in aggregate ($n = 115$ students) to see the consistency of the effectiveness of the virtual reality framework. Data analysis was conducted using IBM SPSS Statistics software to evaluate the validity, practicality, and effectiveness of the developed learning framework. Descriptive statistics were used to analyze the validity and practicality data obtained from expert validation sheets and student response questionnaires. The results were converted into percentage scores and interpreted using predefined feasibility criteria. To assess the effectiveness of the framework, students' conceptual understanding was analyzed using normalized gain (N-Gain) based on pretest and posttest scores. Prior to hypothesis testing, the normality of the data distribution was examined using the Shapiro Wilk test. For normally distributed data, paired sample t-tests were performed to determine whether there were significant differences between pretest and posttest scores. For data that did not meet normality assumptions, the Wilcoxon signed-rank test was applied as a non-parametric alternative. In addition, effect size analysis was conducted to measure the magnitude of the learning impact. Cohen's d was used for parametric data, while effect size r was calculated for non-parametric data. These analyses provided a more comprehensive interpretation of the effectiveness of the developed learning framework.

3. RESULTS AND DISCUSSION

3.1. Expert Validation Results

The results of expert validation of virtual reality-based learning media on Kinematics material indicate that the developed product has a very good level of feasibility. The content feasibility aspect obtained an average score of 91.67%, while the presentation aspect obtained a score of 83%. The linguistic aspect obtained an average score of 92%, while the media aspect obtained a score of 88.89%. Overall, the average total validation result reached 88.89%, which is included in the very feasible category. These results indicate that the developed Virtual Reality-based learning media has met the feasibility standards in terms of content, presentation, language, and media display. Thus, the media can be used in the learning process after making several minor improvements according to the suggestions of the validators. The results of expert validation of virtual reality-based learning media on Fluids material indicate that the developed product meets the very good feasibility criteria. The content feasibility aspect obtained an average score of 90%, while the presentation aspect obtained a score of 85%. The linguistic aspect obtained an average score of 92%, while the media aspect obtained a score of 92.22%. Overall, the average total validation result reached 89.81%, which is included in the very feasible category. This result

indicates that the developed virtual reality-based learning media has met the feasibility standards in terms of content, presentation, language, and media display. Thus, the developed media can be used in the learning process by making some minor improvements according to the suggestions of the validators. The results of expert validation of the virtual reality-based learning media on the particle dynamics material show that the developed product has a very high level of feasibility. The content feasibility aspect obtained an average score of 100%, while the material accuracy aspect obtained a score of 97%. The presentation technique aspect obtained a score of 100%, while the presentation support aspect obtained a score of 92%. In addition, the media aspect obtained an average score of 96%, and the language aspect obtained a score of 100%. Overall, the average total validation result reached 97%, which is included in the very feasible category. This result indicates that the developed Virtual Reality-based learning media has met the feasibility standards in terms of content, presentation, media display, and language. Thus, the media is considered very suitable for use in the physics learning process after minor improvements were made based on suggestions from the validators.

Table 3. Comparison table of virtual reality learning media validation results on three physics materials

Assessment Aspects	Kinematics (%)	Fluid (%)	Particle Dynamics (%)
Content Eligibility	91.67	90.00	100.00
Presentation	83.00	85.00	100.00
Language	92.00	92.00	100.00
Media	88.89	92.22	96.00
Average Validity	88.89	89.81	97.00
Category	Very Feasible	Very Feasible	Very Feasible

The expert validation results show that the developed Virtual Reality-based learning media has a very high level of feasibility for all tested materials. The media for Kinematics obtained an average validity of 88.89%, while the media for Fluids obtained a value of 89.81%. Meanwhile, the media for Particle Dynamics obtained the highest validity value of 97%. When viewed based on the assessment aspects, the linguistic aspect shows high consistency in all materials with a value above 92%. The media aspect also obtained a high value, especially for Particle Dynamics which reached 96%, indicating that the visual design and appearance of the developed media have met the learning feasibility standards. Overall, all developed media are in the very feasible category, so they can be used in the physics learning process after making several minor improvements according to the validator's suggestions.

3.2. Student Response Results (Practicality)

The results of the student response questionnaire regarding the use of virtual reality-based learning media on Fluid material show that the developed media received a very positive response. The linguistic aspect received the highest score of 92.05%, indicating that the language used in the media is easy for students to understand. Meanwhile, the media design aspect received a score of 90.46%, the media benefits aspect 90.87%, the presentation aspect 91.92%, and the ease of use aspect 91.54%. Overall, the average total student response reached 91.37%, which is included in the very good category.

These results indicate that the developed Virtual Reality-based learning media has a high level of practicality and is easy for students to use in the learning process. The results of the student response questionnaire regarding the use of Virtual Reality-based learning media on Particle Dynamics material show that the developed media received a very positive response from students. The presentation aspect of the material received a score of 97%, while the media display aspect received a score of 98%. High scores in both aspects indicate that the developed media is able to present the material clearly and has an attractive visual appearance that is easy for students to understand.

Overall, the average total student response reached 98%, which is included in the very good category. This result indicates that the developed virtual reality-based learning media has a very high level of practicality and provides an interesting learning experience for students. The results of the student response questionnaire regarding the use of virtual reality-based learning media in kinematics material show that the developed media received a positive response from students.

The presentation aspect obtained a score of 88%, while the media design and media benefits aspects each obtained a score of 85%. The ease of use aspect obtained a score of 86%, and the linguistic aspect also obtained a score of 86%. Overall, the average total student response reached 86%, which is included in the very good category. This result indicates that the developed Virtual Reality-based learning media has a good level of practicality and can be used effectively in the physics learning process. While the results indicate high levels of practicality, a more careful interpretation is required. It is important to note that the practicality results in this study are based on students' self-reported perceptions of the learning experience. Therefore, the findings primarily reflect perceived practicality rather than objective measures of usability or implementation efficiency. Based on the results above, the results of the students' responses were obtained.

Table 4. Comparative table of student responses to three materials

Material	Average Response (%)	Category
Kinematics	86.00	Very good
Fluid	91.37	Very good
Particle Dynamics	98.00	Very good

When comparing materials, student responses showed an increasing trend from Kinematics to Particle Dynamics. Kinematics achieved an average response rate of 86%, while Fluids achieved 91.37%, and Particle Dynamics reached 98%. Although the average student responses appear to increase across the three cohorts, this trend should be interpreted cautiously. The observed differences may not necessarily indicate that the framework is more effective or engaging for more complex materials. Instead, they may reflect variations in cohort characteristics, differences in instructional delivery, or the inherent nature of the subject content. Therefore, no causal conclusion can be drawn regarding the relationship between material complexity and the level of student engagement within this study. To further examine the impact of the integrated Kuula-based virtual reality framework on students' learning outcomes, an analysis of conceptual understanding improvement was conducted using the Normalized Gain (N-Gain) index. The results are presented in Table 5.

Table 5. Improvement of students' conceptual understanding based on n-gain

Cohort	n	Mean Pretest	SD Pretest	Mean Posttest	SD Posttest	N-Gain	Category
Kinematics	36	28.36	9.77	88.19	8.04	0.85	High
Fluid	39	29.49	11.85	86.86	9.42	0.81	High
Particle Dynamics	40	28.25	13.77	93.50	6.72	0.87	High
Aggregate (Total)	115	28.68	11.84	89.63	8.16	0.84	High

The analysis of students' conceptual understanding improvement based on the Normalized Gain (N-Gain) index shows that learning using the integrated kuula-based virtual reality framework provides significant improvements across the entire cohort. In the Kinematics material, the average pretest score of 28.36 increased to 88.19 in the posttest with an N-Gain value of 0.85, which is included in the high category. In the fluid material, the average pretest score of 29.49 increased to 86.86 in the posttest with an N-Gain value of 0.81, which is also in the high category. Meanwhile, in the Particle Dynamics material, the average pretest score of 28.25 increased to 93.50 in the posttest with an N-Gain value of 0.87, which is included in the high category. In aggregate, the average pretest score for all students was 28.68, while the average posttest reached 89.63, with an N-Gain value of 0.84, which is in the high category. These results indicate that the developed virtual reality-based learning framework is effective in improving students' conceptual understanding of various physics topics. To ensure the appropriateness of subsequent parametric statistical analyses, the distribution of the pretest and posttest data was first examined using a normality test. The results of the normality analysis are presented in Table 6.

Table 6. Normality test results

Cohort	p-value Pretest	p-value Posttest	Distribution	Tests Used
Kinematics	0.080	0.026	Abnormal	Wilcoxon Signed Rank Test
Fluid	0.252	0.314	Normal	Paired Sample t-test
Particle Dynamics	0.009	<0.001	Abnormal	Wilcoxon Signed Rank Test

The Shapiro Wilk normality test indicated that the data distribution for the Fluids cohort was normal ($p > 0.05$), while the kinematics and particle dynamics cohorts showed non-normal distributions ($p < 0.05$). Therefore, a paired sample t-test was applied to the Fluids cohort, while the Wilcoxon signed-rank test was used for the Kinematics and Particle Dynamics cohorts. The statistical results showed a significant difference between pretest and posttest scores across all cohorts ($p < 0.05$), indicating that the implementation of the integrated Kuula-based virtual reality framework significantly improved students' conceptual understanding. The calculated effect sizes indicate a strong educational impact across all cohorts. The Kinematics cohort showed a large effect size ($r = 0.91$), the fluids cohort demonstrated a very large effect size ($d = 1.59$), and the particle dynamics cohort showed a large effect size ($r = 0.88$). These results indicate that the implementation of the framework had a substantial effect on improving students' conceptual understanding. The results of these difference tests are presented in Table 7.

Table 7. Difference test results (paired-sample t-test and wilcoxon signed-rank test)

Cohort	t / Z Value	Sig. (p)
Kinematics	5.456	<0.001
Fluid	9.902	0.001

The results of statistical analysis were conducted to determine the difference between pretest and posttest scores after the implementation of the integrated kuula-based virtual reality framework in physics learning. Based on the results of statistical tests, all cohorts showed a significant difference between scores before and after learning. In the kinematics material, the Wilcoxon test results showed a statistical value of $Z = 5.456$ with a significance value of $p < 0.001$. These results indicate that there is a significant difference between students' pretest and posttest scores after the implementation of virtual reality-based learning. In the fluid material, the results of the paired sample t-test showed a value of $t = 9.902$ with a significance value of $p = 0.001$. A significance value smaller than 0.05 indicates that there is a significant increase in student learning outcomes after participating in learning using the developed virtual reality framework. Meanwhile, in the particle dynamics material, the Wilcoxon test results showed a statistical value of $Z = 5.543$ with a significance value of $p < 0.001$. These results also indicate that there is a significant difference between students' pretest and posttest scores. Overall, the statistical analysis results indicate that the implementation of the integrated kuula-based virtual reality framework significantly improved students' conceptual understanding of the three physics topics studied. This finding reinforces the results of the N-Gain analysis, which was in the high category, as well as the effect size value, which indicated a strong learning impact [43], [44]. The results of the effect size analysis are presented in Table 8.

Table 8. Effect Size Analysis Results

Cohort	Test	Statistics	p-value	Effect Size	Category
Kinematics	Wilcoxon	$Z = 5.456$	<0.001	$r = 0.91$	Large
Fluid	Paired t-test	$t = 9.902$	0.001	$d = 1.59$	Very large
Particle Dynamics	Wilcoxon	$Z = 5.543$	<0.001	$r = 0.88$	Large

Statistical analysis showed a significant difference between pretest and posttest scores across all cohorts after the implementation of the integrated kuula-based virtual reality framework. The Wilcoxon signed-rank test results showed a significant increase in the Kinematics cohort ($Z = 5.456$; $p < 0.001$) and the Particle Dynamics cohort ($Z = 5.543$; $p < 0.001$). Meanwhile, in the Fluids cohort, a paired sample t-test also showed a significant difference between pre- and post-learning scores ($t = 9.902$; $p = 0.001$). These findings indicate that the improvement in learning outcomes was not statistically coincidental, but rather a consequence of the implemented learning intervention. In addition to statistical significance, effect size analysis demonstrated the magnitude of the resulting learning impact. The Kinematics cohort showed a large effect size ($r = 0.91$), while the Particle Dynamics cohort also showed a large effect size ($r = 0.88$). In the fluid cohort, a very large effect size ($d = 1.59$) was obtained, indicating that the learning intervention had a very strong influence on improving students' conceptual understanding. The large effect size values in all three cohorts indicate that the improvement in learning outcomes is not only statistically significant but also has substantial educational significance. Overall, the consistency of the improvement results across various physics topics indicates that the developed virtual reality-based learning framework is not only effective in specific material contexts but also has potential transferability across topics. These findings strengthen the argument that the integration of pedagogically designed immersive technology can support a deeper concept construction process in physics learning [45].

The findings of this study demonstrate a consistent improvement in students' conceptual understanding across all three cohorts. One notable finding is that the Particle Dynamics cohort achieved the highest posttest scores and N-Gain values. This may be attributed to the abstract nature of particle dynamics concepts, which involve forces, motion interactions, and vector relationships that are difficult to visualize using traditional methods [46]. The immersive 360° virtual reality environment likely provided more concrete and contextual representations, thereby reducing cognitive load and facilitating deeper understanding. This aligns with Cognitive Load Theory, which emphasizes that well-designed visual representations can enhance learning efficiency [22], [47]. However, differences among cohorts should be interpreted cautiously, as they may also be influenced by factors such as prior knowledge, cognitive readiness, engagement levels, and classroom dynamics rather than solely by the instructional framework [48].

The novelty of this research lies in the systematic integration of immersive virtual reality within a multi-component digital learning ecosystem that includes PhET simulations, digital flipbooks, and a problem-based learning approach. Unlike previous studies that treat virtual reality as a standalone tool, this study demonstrates that learning effectiveness emerges from the synergy between immersive visualization, interactive exploration, and structured pedagogy [49]. The implications of this research suggest that the successful implementation of virtual reality in education depends not only on technological sophistication but also on its alignment with pedagogical design and cognitive principles. This integrated approach provides a practical model for designing immersive learning environments that support conceptual understanding in physics [25].

Despite these positive findings, several limitations of this research should be acknowledged. The use of a one-group pretest posttest design introduces potential internal validity threats, including testing effects, novelty

effects, and teacher related influences [50]. Additionally, the multi-component nature of the intervention makes it difficult to isolate the specific contribution of each element. The study was also conducted in a single school using a convenience sampling technique, which limits the generalizability of the findings. Therefore, future research is recommended to employ experimental designs with control groups, involve multiple institutions, and examine long-term learning outcomes. Overall, this study highlights that the effectiveness of virtual reality in education is not solely determined by immersion, but by its pedagogical integration within a structured and theory-driven learning environment [51].

The results of this study indicate that the integrated kuula-based virtual reality framework is associated with consistent improvements in students' conceptual understanding across three different physics topics [44]. The increase in N-Gain values and large effect sizes suggests a strong learning impact within the studied context. Theoretically, this improvement can be explained through cognitive load theory, where immersive 360° video environments help reduce extraneous cognitive load by presenting physics phenomena in a contextual and realistic manner [22]. This supports students in constructing more accurate mental representations of abstract concepts. In addition, the integration of virtual reality with textual explanations and interactive simulations aligns with the cognitive theory of multimedia. Learning and dual coding theory, which emphasize the importance of combining visual and verbal representations [52]. The findings are also consistent with the Cognitive Affective Model of Immersive Learning (CAMIL), suggesting that immersive environments can enhance both cognitive and affective engagement when supported by structured instructional design [19].

The novelty of this research lies in the systematic integration of immersive virtual reality within a multi-component digital learning ecosystem, rather than treating virtual reality as a standalone instructional tool [21]. This framework combines Kuula-based virtual reality, PhET simulations, digital flipbooks, Google Classroom, and ClassPoint within a problem-based learning approach [53]. The implications of this research indicate that the effectiveness of virtual reality in education depends not only on the technology itself, but on how it is pedagogically integrated with other learning tools and strategies [50]. Furthermore, this study demonstrates that immersive learning can be implemented using accessible web-based platforms, without requiring expensive hardware such as head-mounted displays, thereby increasing its feasibility in diverse educational settings, including resource-limited contexts [55], [56].

Despite these promising findings, several limitations of this research should be acknowledged. The study employed a one-group pretest–posttest design without a control group, which limits the ability to establish causal relationships [57]–[59]. Additionally, the research was conducted in a single school using a convenience sampling technique, which restricts the generalizability of the results. The multi-component nature of the intervention also makes it difficult to isolate the specific contribution of each element. Therefore, future research is recommended to use experimental designs with control groups, involve multiple institutions, and examine long-term retention and affective outcomes such as motivation and self-efficacy. Overall, this study highlights that the effectiveness of immersive learning is determined not solely by technological immersion, but by its alignment with pedagogical principles and instructional design.

4. CONCLUSION

This study developed and evaluated an integrated kuula-based virtual reality framework for high school physics learning. The findings indicate that the developed framework demonstrates high levels of validity and practicality based on expert evaluation and student responses. The implementation of the framework was associated with substantial improvements in students' conceptual understanding across the three physics topics studied, as reflected in the N-Gain and effect size results. These findings suggest that the integration of immersive virtual reality with supporting digital tools and structured pedagogical design has the potential to support conceptual learning in physics. However, the results should be interpreted within the context of the study. Due to the use of a one-group pretest posttest design, the absence of a control group, and the implementation within a single school setting, the findings do not provide definitive evidence of causal effectiveness or broad generalizability. Instead, they indicate promising outcomes within the studied context. Future research is recommended to employ more rigorous experimental designs, involve multiple institutions, and examine long-term learning retention to further validate and extend these findings.

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AUTHOR CONTRIBUTIONS

Conceptualization, Eko Risdianto and Joselin Santos; Methodology, Eko Risdianto, Noel Lomerio, and Deshinta Arrova Dewi; Software, Ressti Nurfitriani and Jeni Fitria; Validation, Joselin Santos, Noel Lomerio, and M. Esad Kuloglu; Formal Analysis, Eko Risdianto and Sultan Hammad Alshammari; Investigation, Ressti Nurfitriani, Jeni Fitria, and Deshinta Arrova Dewi; Resources, M. Esad Kuloglu and Sultan Hammad Alshammari; Data Curation, Ressti Nurfitriani and Jeni Fitria; Writing – Original Draft Preparation, Eko Risdianto; Writing Review & Editing, Joselin Santos, Noel Lomerio, and Sultan Hammad Alshammari; Visualization, Ressti Nurfitriani; Supervision, Eko Risdianto; Project Administration, Eko Risdianto.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study. Prior to participation, all students were provided with a detailed explanation of the study's objectives, procedures, potential risks, and benefits. Participation was entirely voluntary, and all participants agreed to take part in the study and signed a written informed consent form prior to data collection.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper. The authors are responsible for the content and writing of this article.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

During the preparation of this work, the authors used AI-assisted technology to support language improvement and clarity. All outputs were carefully reviewed and edited by the authors, who take full responsibility for the content of this publication.

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