Affordable Immersive Learning: Integrating Low-cost Virtual Reality and Problem-based Learning to Enhance Science Comprehension and Digital Literacy

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***Abstract*—This study examines the effectiveness of integrating low-cost Virtual Reality (VR) into Problem-Based Learning (PBL) in supporting elementary students' visualization of science concepts and development of digital literacy. Despite growing interest in immersive technologies for education, few studies have examined the combined use of affordable VR and PBL to simultaneously enhance digital literacy and science comprehension in resource-constrained primary school settings. Using a quasi-experimental design with purposive cluster sampling and random allocation of schools to conditions, the study involved 136 students from six public schools in Semarang, Indonesia. The experimental group (n = 68) learned the Human Digestive System using Google Cardboard headsets in a PBL-VR model, while the control group (n = 68) received conventional instruction. Statistical analysis using the Mann-Whitney U test revealed significant differences in post-test scores between groups; the experimental group recorded a mean gain of 13.77 in digital literacy and 17.62 in science comprehension, compared to the control group's gains of 3.44 and 7.83, respectively. Effect size analysis indicated a medium effect on digital literacy (r = 0.42) and a small-to-medium effect on science comprehension (r = 0.27). These findings suggest that integrating low-cost semi-immersive VR within a PBL framework may effectively support students' digital literacy and science understanding, offering a potentially scalable approach for technology-enhanced learning in resource-constrained educational settings in developing countries.**

***Keywords*—digital literacy, elementary education, human digestive system, low-cost virtual reality, problem-based learning**

I. Introduction

Today's digital world is pervasive, fundamentally shaping how we learn, work, and communicate. The capacity to proficiently employ digital technology requires significant attention, as individuals must develop skills for both consuming and producing content in the digital domain, digitally build and represent themselves; communicate ethically over the Internet [1, 2]. Research indicates that technology has made learning more flexible, interactive and productive in ways that offer an unprecedented platform for the use of student-centered pedagogical approaches [3, 4]. The increasing convergence of smartphones, computers and tablets with immersive technologies such as Virtual Reality (VR) is accelerating the drive towards learner-centred instruction that allows near limitless access to information while providing flexibility in terms of time and location [5, 6].

From an early age students need digital literacy skills to cope with constant digital change. Digital literacy, often referred to as the fourth fundamental skill alongside reading, writing, and numeracy [7], is described as the ability to retrieve, evaluate and produce information using digital content. Yet digital divides persist, as underscored during the COVID-19 pandemic, when remote learning revealed marked differences in access to technology and digital fluency [8, 9]. A recent meta-analysis found that classroom-based digital literacy programs showed slightly higher positive effects on children and adolescents (SMD = 0.16), with a larger effect on primary school students [10]. One approach to bridge this gap at the primary school level is enhancing digital literacy, which, following Tsvetkova *et al.* [11], refers to a child's competence in understanding and using various digital technologies, including hardware concepts, software applications, internet search strategies, online safety, and digital communication etiquette. The adoption of Information and Communication Technologies (ICTs) and immersive technological learning methods including VR may also facilitate the integration of digital literacy practices into elementary education [12, 13].

The 21st-century educational paradigm positions students at the center of the learning process, emphasizing the integration of ICT and immersive technologies such as VR to develop technological literacies [14, 15]. One pedagogical approach aligned with 21st-century learning is Problem-Based Learning (PBL) which fosters communication, creativity, collaboration and critical thinking [16, 17]. Evidence from a recent meta-analysis indicates that PBL has a significant impact on students' 21st-century skills, with effect sizes ranging from 0.617 to 1.72 [18]. PBL significantly affects students' self-reported perceptions of digital literacy, instrumentality and technology-related engagement as measured by attitude towards use of technology and critical thinking [19, 20]. Nonetheless, obstacles persist, including the need for authentic real-world problems and the difficulty of providing immersive learning experiences within traditional classroom settings [21].

These issues can be addressed by integrating Virtual Reality into Problem-Based Learning. Unlike other digital tools such as educational apps or web-based platforms that offer primarily two-dimensional interaction, VR provides

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three-dimensional virtual environments that allow students to engage with complex concepts through embodied, first-person exploration, thereby simultaneously developing digital operational skills (navigating interfaces, manipulating controls) [12, 22]. This dual affordance makes VR uniquely suited as a bridge between digital literacy development and science concept visualization. One recent systematic review indicates that VR is an effective tool to increase student motivation, skill acquisition and interaction especially in relation to 21st-century skills in P-12 education [23]. Research has shown that VR-based learning environments can enhance students' cognitive engagement, critical thinking, and problem-solving through immersive experiences [24, 25]. Elementary school students have great advantages when they learn scientific materials through PBL and VR, as hands-on practice significantly enhances conceptual understanding [13, 21].

Combining the strengths of both approaches, this study proposes a PBL-based model integrating VR to support fifth graders in Semarang City in understanding the human digestive system and developing digital literacy. Passive learning environments and the memorizing of scientific data cause many students to struggle with understanding scientific concepts, particularly for abstract concepts like the Human Digestive System [26, 27]. A study indicates that 26.0% of students hold misconceptions about digestive processes, including beliefs about physical and chemical digestion and confusion about the functions of digestive organs [26]. The process of food digestion is internal and difficult for students to visualize [28]. The PBL-VR is intended to encourage active participation during the learning process so that students make meaningful and immersive inquiries into scientific topics, addressing these pervasive misconceptions through visualization of internal biological processes that are not directly visible [12, 13].

While the integration of PBL with various digital technologies has been explored in prior research [21, 29, 30], several gaps remain in the literature. First, most studies examining VR in education have employed high-end, expensive equipment, leaving open the question of whether low-cost, smartphone-based VR solutions can produce comparable educational benefits in resource-constrained settings [31, 32]. Second, few studies have simultaneously assessed both digital literacy and science comprehension outcomes within a single PBL-VR intervention, particularly at the primary school level. Third, research on technology-enhanced PBL in developing countries, where infrastructure limitations present unique implementation challenges, remains underrepresented in the international literature. This study addresses these gaps by evaluating the effectiveness of a PBL model integrated with affordable smartphone-based VR technology (Google-Cardboard-compatible) in simultaneously enhancing digital literacy and science comprehension among fifth-grade students in Semarang, Indonesia. The approach responds to recent demand for low-cost VR solutions that can be used in schools with limited technology infrastructure [31].

The primary objective of this research is to evaluate the effectiveness of a Problem-based Learning model assisted by low-cost Virtual Reality in enhancing elementary students' digital literacy and science comprehension. Specifically, this research examines the following questions:

(1) To what extent does integrating problem-based learning with virtual reality technology contribute to the enhancement of elementary students' digital literacy?
(2) To what extent does integrating problem-based learning with virtual reality technology contribute to improving elementary students' comprehension of science concepts, specifically the Human Digestive System?

The research was conducted in The City of Semarang, located in the Central Java province, Indonesia with fifth-grade students as samples. Semarang was selected as the research site due to its diverse educational landscape and the availability of schools with infrastructure suitable for VR-based interventions. The focus on fifth grade children (average age of 10–11 years) corresponds to their stage of cognitive development that involves increasing capacity for abstract reasoning, making it possible for them to engage with complex biological themes such as the Human Digestive System.

This study has the potential to contribute empirical evidence on the effectiveness of combining Problem-Based Learning with affordable Virtual Reality technology for elementary science education. As VR technology further demonstrates its potential in science education, especially for promoting engagement and conceptual understanding, the question of how affordable VR solutions can be effectively implemented gains greater importance in achieving educational equity [33, 34]. The results may inform educational practice and policy to enrich the young learners' digital literacy and science understanding, especially in developing countries where high-end VR equipment implementation is prohibitively expensive. Furthermore, this research can support the trend of technology-enhanced learning in Indonesian education, particularly in urban areas like Semarang City.

II. Literature Review

A. Digital Literacy in Primary School

The digitization of information and communication has been regarded as part of the Fourth Industrial Revolution [35], having implications for business, government, and people's everyday life. Many scholars argue that digital competencies, literacy, abilities, and internet skills are necessary in contemporary world [36]. In response to the increasing significance of digital literacy as a critical skill for children and adolescents in today's education system, school-based interventions have demonstrated moderate, positive impacts on the development of digital literacy [10]. Digital literacy is important for the future of students and their communities since it enables informed decisions related to interacting with digital media and promotes critical thinking [37].

In the post-pandemic era, digital resources and virtual platforms have become increasingly important in the educational process, and the usage of smartphones and tablets has become a popular way to improve primary school students' digital literacy [38]. During the pandemic, problems with digital literacy manifested as difficulties in online communication and a general lack of proficiency with technology [39], difficulty in evaluating online information [40], and restricted access to library materials [41]. The current state of digital literacy instruction represents both strides made in equipping students with vital competencies and areas not yet addressed by current practice [42]. In the United States, for example, only a handful of states currently require digital literacy instruction [43].

Resolving the problem of digital deficiency in education should be a priority for national governments to ensure that ICT projects on digitization of education progress. Integration of technology (e.g., Virtual Reality) into education presents several opportunities to enhance digital literacy. Teachers could use learning approaches such as Problem-Based Learning supported by VR to develop digital literacy [44]. The objective of teaching digital literacy is to enable students to use digital media in ways that make them more engaged, creative, productive and innovative.

The relevance of teaching and learning digital literacy has been increasingly emphasised in Indonesia, amidst rapid technological development. Studies across Indonesian cities, such as Semarang city in Central Java, have indicated that there is a wide gap of digital literacy skills influenced by socioeconomic status and technology access [45, 46]. This reality emphasizes the need for developing effective pedagogical strategies that can improve students' digital literacy and bridge existing gaps [47].

B. Problem-based Learning and Science Education

Many educators recognize that Problem-Based Learning (PBL) is an effective approach to enhance students' learning performance [48]. PBL, as an active learning approach, allows students to be presented with real-world problems in need of investigation and solution. A meta-analysis of 48 studies showed that the general effect size of PBL is 1.063, suggesting that it had an overall significant effect on science education, with PBL approximately 86% more effective than traditional teaching methods in improving students' academic performance across different science subjects [49].

PBL represents a significant evolution in active learning methodologies. Students confront real-world problems, and class time is used for more complex cognitive tasks in interactive spaces [50]. Contemporary studies of problem-based learning reveal that students in PBL curricula outperform their counterparts taught under traditional models of instruction in terms of knowledge, attitudes, behaviors and beliefs [48].

The five steps of Problem-Based Learning provide a systematic framework: (1) introducing students to the problem, (2) preparing them for study, (3) supporting both independent and group investigations, (4) creating and displaying artifacts and exhibits, and (5) reflecting on and assessing the problem-solving process [51]. Each phase builds the problem-solving, collaboration and critical thinking skills. In the context of science education on the Human Digestive System, PBL allows the linking and application of theoretical concepts for solving real-life health and nutritional problems.

C. Virtual Reality in Science Education

Scientific inquiry drives both the development of new technologies and our understanding of the natural world. Students develop critical thinking and problem-solving skills through science instruction. According to a meta-analysis based on 37 studies (published from 2000 to 2022), virtual reality had a moderate positive effect on students' practical skills in STEM fields ($g = 0.477$) [22].

Science learning is challenging, especially when dealing with abstract topics such as the Human Digestive System; students often become less engaged and develop misconceptions [26]. Virtual reality presents opportunities for science education where students can experience three-dimensional, interactive environments in which they learn about concepts that would otherwise be invisible and unattainable [52, 53]. With VR, students can experience virtual field trips and travel within the human body; surveying digestion process, learning about organs in ways superior to traditional approaches [54].

Newer VR tools are less expensive and more accessible for classroom use. Smartphone and cardboard viewer-based mobile VR solutions have made it possible for underfunded schools to bring VR-based learning into the classroom [55], providing financially viable and versatile solutions while maintaining educational value comparable to higher-end systems [56, 57]. Studies conducted in various countries have demonstrated positive outcomes when VR is integrated into elementary science education [58], including improved spatial understanding [59], increased motivation, and better retention of scientific concepts [60]. However, successful implementation requires careful instructional design that aligns VR experiences with learning objectives and provides adequate scaffolding for young learners.

D. Theoretical Framework: Constructivism, Cognitive Load Theory, and Multimedia Learning Theory

The theoretical foundation of this study draws on three complementary frameworks: constructivist learning theory, Cognitive Load Theory (CLT), and the Cognitive Theory of Multimedia Learning (CTML).

Constructivist learning theory posits that learners construct knowledge through active engagement with their environment [61, 62]. Both PBL and VR align with constructivist principles, as they create authentic task environments where students build understanding through interaction and exploration. Research on constructivist learning environments has found that they promote both intrinsic and extrinsic motivation, with students' learning strategies being significantly enhanced when studying through constructivist approaches [63].

Sweller's Cognitive Load Theory [64] provides a critical lens for understanding how immersive technologies interact with learning. CLT identifies three types of cognitive load: intrinsic load (inherent complexity of the material), extraneous load (caused by poor instructional design), and germane load (devoted to schema construction and learning). In the context of VR-based learning, the immersive nature of VR environments may increase extraneous cognitive load through sensory overload if not carefully designed [65]. The PBL-VR model in this study addresses this concern by separating the VR exploration phase (pre-class, 30 min) from PBL activities (in-class, 90 min), thereby managing cognitive load through temporal sequencing. The VR phase focuses on visual-spatial processing of digestive system structures, while the subsequent PBL phase shifts attention to verbal-analytical processing through group discussion and problem-solving, allowing germane cognitive load to be distributed across both phases.

Mayer's cognitive Theory of Multimedia Learning [66] further supports the PBL-VR design. CTML proposes that learners process information through dual channels (visual-spatial and auditory-verbal) with limited capacity. The PBL-VR model leverages this dual channel processing, the VR component engages the visual-spatial channel through 3D anatomical models and animated digestion sequences, while the PBL component activates the auditory-verbal channel through narrated explanations, group discussions, and collaborative problem-solving. This sequential multimodal approach aligns with Mayer's modality principle, potentially optimizing cognitive resource allocation and reducing the risk of cognitive overload that may occur when both channels are simultaneously overwhelmed [67].

E. The Integration of PBL and VR: Implications for Digital Literacy and Science Comprehension

Past research has considered problem-based learning with various technologies. The combination of collaborative learning and immersive technology has been associated with enhanced motivation to study [29]. Studies on technology-based PBL have revealed significant improvements in academic achievements, with learners participating in technology-assisted PBL performing better than those following traditional learning models [30].

Gamified virtual reality learning environments have been found to offer richer levels of motivation, engagement and interactivity than traditional learning contexts, opening up new opportunities for personalised and collaborative education [29]. Meta-analytic research on VR in primary school environments found that students trained with VR displayed significantly higher academic performance than those taught by traditional methods (with a medium effect size, ~0.64) [68]. VR learning may increase recall and understanding of the relationship between concepts, enabling students to apply their knowledge in other situations [23, 59].

While existing studies demonstrate the individual merits of PBL and VR, critical examination reveals that most research has focused on either PBL with non-immersive technologies or VR without structured pedagogical frameworks. Few studies have examined the combined effect of PBL and VR on both digital literacy and scientific understanding at the primary school level, particularly using affordable VR solutions in developing country contexts. Moreover, existing literature lacks systematic evaluation of how the temporal sequencing of VR exploration followed by PBL activities may optimize cognitive load distribution, a gap this study seeks to address.

The PBL-VR model designed for this study (Fig. 1) comprises two main phases: (A) Pre-Class Phase (VR Introduction and VR Exploration) and (B) In-class Phase (PBL Activities). In the VR exploration stage, students learn how to use VR headsets and then take a virtual journey through the human digestive system, observing organ structures and digestion processes. The in-class sequence follows the five stages of PBL [51]: (1) Problem Orientation, which introduces students to real-life scenarios related to digestion and nutrition; (2) Organizing for Study, where students form groups and determine learning needs; (3) Investigation, where students gather data using multiple sources including their VR experiences; (4) Developing Artifacts, where students create models or presentations demonstrating solutions; and (5) Analysis and Evaluation, where students reflect on and assess the problem-solving process.

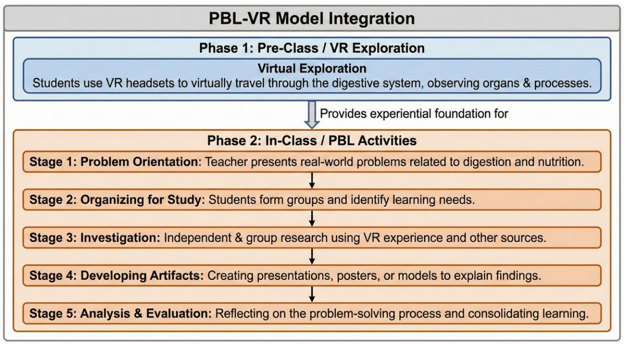

Fig. 1. Problem-based learning assisted by virtual reality model.

III. MATERIALS AND METHODS

A. Research Design

This research employs a quasi-experimental design using purposive cluster sampling followed by random allocation of schools to conditions. Six elementary schools meeting predetermined inclusion criteria were purposively selected, and then randomly assigned (three schools each) to either the experimental or control condition. Because random assignment occurred at the school level rather than at the individual student level, a practical necessity since individual randomization within intact classrooms was neither feasible nor ethical, the design is described as quasi-experimental with school-level random assignment. This design is common in educational research where classroom-level implementation of interventions precludes individual randomization [69].

The non-equivalent control group aspect of this design arises from the fact that, despite random assignment of schools to conditions, individual students within those schools were not randomly assigned, they were part of existing intact classrooms. The school-level randomization helps reduce selection bias at the institutional level, but differences between student populations across schools may still exist. We acknowledge that because assignment occurred at the school level with only six schools (three per condition), treating individual students as independent units in statistical analyses may overstate significance. We address this through a sensitivity analysis at the cluster level (reported in Results) and through cautious interpretation of findings.

The study aimed to investigate whether the combined PBL-VR instructional package could be associated with greater gains in student performance compared to conventional instruction. This practical perspective mirrors educational research practice, in which instructional innovations are implemented as integrated packages rather than isolated variables [69].

Data collected included use of instruments such as tests, observations and questionnaires. Researchers in the fields of education, science education and evaluation reviewed the research instruments before use. Table 1 specifies the research design.

Table 1. Research design

Groups	Pretest	Treatment	Posttest
Experimental	O_1	X_1	O_2
Control	O_3	X_2	O_4

Note: O_1 & O_3 = Pretest; O_2 & O_4= Posttest; X_1 = Problem-Based Learning assisted by Virtual Reality (PBL-VR) model; X_2 = Conventional learning model.

The experimental group was taught through the PBL model with Virtual Reality (PBL-VR) on Human Digestive System. The control group received instruction by means of a conventional learning models that predominantly included teacher-centered lectures, textbook based activities and traditional visual aid materials (e.g., posters, drawings). Importantly, the control group did not use any digital resources or technology-based tools during intervention period. Both groups covered the same learning objectives and material content based on Indonesian national curriculum for fifth grade students.

B. Participants

The sample was selected through purposive cluster sampling with the school as the unit of assignment. Six schools meeting the inclusion criteria were selected, and then randomly allocated to experimental and control conditions at the school level. Intact classroom groupings characterized the study; individual students were not randomly assigned.

To examine baseline equivalence, pretest scores in both digital literacy and science comprehension were compared between experimental and control group using the Mann-Whitney U test. Results showed no significant differences in pretest scores for digital literacy (U = 2198.5, $p = 0.618$) or science comprehension (U = 2254.0, $p = 0.780$), suggesting adequate baseline equivalence between groups.

Fifth grade students from six public elementary schools in the city of Semarang, Central Java, Indonesia participated. Schools were selected based on the following criteria: (1) having a "B" (good) or higher rating from Indonesia's National Accreditation Board; (2) computer lab and/or multimedia room facilities; (3) reliable internet connections and appropriate hardware; (4) willingness of the school administration and teachers to participate in this study; and, other determining factors such as similar demographics of students and comparable student outcomes based on previous national exams results.

A total of 136 students participated in this study, comprising 68 students in the experimental group across three schools and 68 students in the control group across another three schools. Table 2 presents demographic characteristics.

Table 2. Demographic characteristics of participants

Characteristics	Category	Experimental ($n = 68$)	Control ($n = 68$)
Gender	Male	27 (39.7%)	29 (42.6%)
	Female	41 (60.3%)	39 (57.4%)
Age (years)	10	28 (41.2%)	31 (45.6%)
	11	40 (58.8%)	37 (54.4%)
Prior VR Experience	Yes	12 (17.6%)	14 (20.6%)
	No	56 (82.4%)	54 (79.4%)

All participants were fifth-grade students aged 10–11 years. Informed consent was obtained from parents or guardians of all participating students. Students with visual impairments or conditions that could be affected by VR use (e.g., epilepsy, severe motion sickness) were excluded from the experimental group and offered alternative learning activities.

C. Intervention: PBL-VR Model

The Problem-Based Learning model assisted by Virtual Reality (PBL-VR) was developed specifically for this study to teach the Human Digestive System to fifth-grade students. The model integrates the five phases of Problem-Based Learning [51] with low-cost, semi-immersive VR technology. The instructional design framework used during the development process was the Analyze, Design, Develop, Implement, and Evaluate (ADDIE) model [70].

During the Analysis phase, learning needs, student characteristics (age, prior VR experience, digital literacy levels), and curriculum requirements were assessed. The Design phase involved mapping PBL stages to VR activities and creating assessment blueprints. In the Development phase, the VR application was built using Unity 3D, PBL materials were created, and expert validation was conducted. The Implementation phase involved teacher training followed by the 4-week classroom intervention. The Evaluation phase encompassed both formative feedback during pilot testing and summative assessment through pre- and post-tests.

The VR application employed in this study was developed using the Unity 3D game engine and provided anatomically correct 3D models of the human gastrointestinal system. Importantly, the app was developed for use with inexpensive smartphone VR headsets (Google Cardboard-compatible) that cost between US$5 and $15 per unit. The VR content consisted of interactive 3D models of the digestive organs (mouth, esophagus, stomach, small intestine, large intestine, liver, pancreas and gallbladder), animated sequences explaining the digestion process, and narrated explanations in Bahasa Indonesia appropriate for fifth-grade students. The user interface of the application can be seen in Fig. 2.

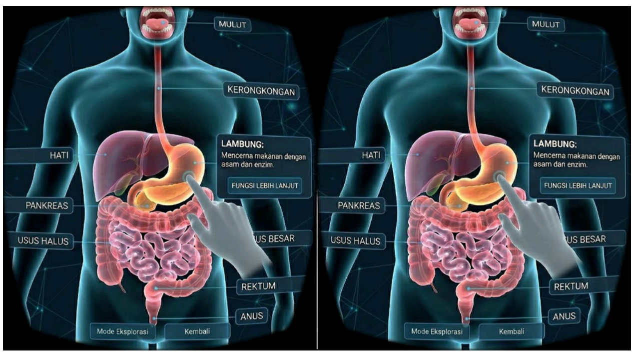

Fig. 2. User interface of the "Human Digestive System" VR application developed using Unity 3D.

The PBL-VR model is composed of two major phases; the VR Exploration Phase and the Classroom PBL Phase. The model implementation is detailed in Table 3.

The problem scenario presented to students was: *"Andi often eats snacks* quickly *without chewing properly. He frequently experiences stomachaches after eating. Recently, he noticed that even though he eats a lot, he feels tired easily. Using what you learned from the VR exploration of the* *digestive system, explain: (a) Why does Andi get stomachaches? (b) What happens to food that is not properly chewed when it enters the stomach and intestines? (c) Why might Andi feel tired even though he eats a lot? (d) What advice would you give Andi about healthy eating habits?"* This scenario required students to apply their VR-based observations of organ functions and digestion processes to a real-world problem.

Table 3. Implementation of the PBL-VR model

Phase	Stage	Activities	Duration	Teacher Role
Phase 1: VR Exploration (30 minutes)	VR Introduction	Students learn how to use VR headsets; safety instructions provided; brief orientation to VR environment	10 min	Demonstrates VR operation; monitors for discomfort
	Virtual Exploration	Students explore the 3D digestive system; observe organ structures; watch animated digestion process; listen to narrated explanations	20 min	Guides exploration; prompts observation questions
Phase 2: Classroom PBL (90 minutes)	Stage 1: Problem Orientation	Teacher presents real-world problems scenario (see below); students connect VR experience to problem	15 min	Presents problem; facilitates discussion
	Stage 2: Organizing for Study	Students form groups of 4-5; identify learning needs based on problem; divide tasks among group members	10 min	Assists group formation; guides task division
	Stage 3: Investigation	Groups conduct research using textbooks, internet resources, and reflections from VR experience	25 min	Facilitates inquiry; provides scaffolding
	Stage 4: Developing Artifacts	Groups create presentations, posters, or models explaining their findings; present solutions to the class	25 min	Monitors progress; provides feedback
	Stage 5: Analysis & Evaluation	Class discussion of solutions; reflection on problem-solving process; teacher consolidates learning	15 min	Leads reflection; provides summative feedback

The intervention was delivered for 4 weeks (2 sessions/week, 8 sessions). Each session lasted approximately 120 min. To control for potential confounding variables, all experimental group teachers received the same standardized training on PBL-VR implementation, including technical VR operation and pedagogical guidance. Teachers followed a structured implementation guide to ensure fidelity.

D. Measurements

This study included two primary instruments: a digital literacy assessment and a science comprehension test focused on the Human Digestive System. Both instruments were developed by the research team and validated by expert panels prior to deployment.

1) Digital literacy assessment

The digital literacy assessment was developed to measure fifth-graders' digital literacy knowledge based on Tsvetkova *et al.*'s [11] conceptual framework for digital literacy in primary school. This framework aligns with the competence areas identified in the European Digital Competence Framework (DigComp 2.2) [71], particularly in the domains of Information and Data Literacy (competence area 1), Communication and Collaboration (competence area 2), and Safety (competence area 4). The VR-related indicators (items 7–9) are mapped to competence area 5 (Problem Solving), specifically sub-competence 5.4 (Identifying digital competence gaps). Although these items assess knowledge-level understanding of VR terminology and functionalities rather than active problem-solving tasks, they measure students' ability to recognize and understand VR technology as a component of their broader digital competence—a prerequisite for identifying gaps in one's own digital skills and knowledge. Table 4 presents the mapping of all assessment indicators to the corresponding DigComp 2.2 competence areas and sub-competences. The complete instrument with scoring key and item-to-framework mapping is provided in the Appendix (Appendix Table A1). The test comprises 17 multiple-choice items. It is important to note that this instrument measures knowledge-based digital literacy rather than performance-based digital skills.

Table 4. Mapping of digital literacy assessment indicators to DigComp 2.2 competence framework

No	Indicators	Items	DigComp 2.2 Competence Area	Specific Competence
1	Understanding of terminology, functionalities, and categories of hardware	1, 2, 3	1. Information and Data Literacy	1.1 Browsing, searching, and filtering data, information, and digital content
2	Understanding of terminology, functionalities, and categories of software	4, 5, 6	1. Information and Data Literacy	1.1 Browsing, searching, and filtering data, information, and digital content
3	Understanding of terminology, functionalities, and categories of virtual reality tools and applications	7, 8, 9	5. Problem Solving	5.4 Identifying digital competence gaps
4	Understanding various browser types and strategies for optimum browser utilization	10, 11	1. Information and Data Literacy	1.1 Browsing, searching, and filtering data, information, and digital content
5	Understanding several methods for obtaining information online	12	1. Information and Data Literacy	1.2 Evaluating data, information, and digital content
6	Understanding the procedures for doing online information searches	13	1. Information and Data Literacy	1.1 Browsing, searching, and filtering data, information, and digital content
7	Understanding security in the utilization of the internet and immersive technologies	14	4. Safety	4.1 Protecting devices; 4.2 Protecting personal data and privacy
8	Understanding etiquette of online communication	15	2. Communication and Collaboration	2.5 Netiquette
9	Understanding ways to save and manage online information	16	1. Information and Data Literacy	1.3 Managing data, information, and digital content
10	Understanding appropriate and inappropriate online content	17	4. Safety	4.3 Protecting health and well-being

2) Scientific comprehension assessment

The science comprehension test was designed to assess students' understanding of Human Digestive System concepts refer to the learning objectives established in Indonesia's national curriculum (Kurikulum Merdeka) for fifth-grade level. The assessment consisted of 15 multiple-choice items based on Bloom's Revised Taxonomy [72]. Table 5 presents the assessment indicators.

Table 5. Assessment instrument for scientific understanding (human digestive system)

Indicators	Item Numbers
Identifying organs of the human digestive system	1, 2, 3
Explaining the function of each digestive organ	4, 5, 6
Describing the sequence of the digestive process	7, 8, 9
Understanding the role of enzymes in digestion	10, 11
Analyzing common digestive system disorders and their causes	12, 13
Applying knowledge to maintain digestive system health	14, 15

3) Instrument validation and reliability

Instrument validation followed a two-stage process:

Stage 1: Expert review for content validity evidence. Three academics specializing in educational technology, science education, and assessment evaluated both instruments on four dimensions: (1) item-indicator alignment; (2) grade-level appropriateness (comprehensibility for fifth-graders); (3) correct Bahasa Indonesia language and spelling; and (4) conceptual accuracy. Items were revised based on expert recommendations until consensus was reached.

Stage 2: Pilot testing for item discrimination and internal consistency. Following expert validation, both instruments were pilot-tested with 32 fifth-grade students from a school not included in the main study. Item discrimination was assessed using the Pearson product-moment correlation coefficient (r_{xy}) between each item score and the total test score. At a significance level of 0.05, items were considered acceptable when the r_{xy} value exceeded the critical table value of 0.349 (n = 32). Internal consistency was assessed using Cronbach's alpha. The digital literacy test yielded α = 0.861 and the science comprehension test yielded α = 0.872, both indicating high reliability.

E. Data Analysis

The data analysis in this study involved several steps using IBM SPSS Statistics version 26:

1) Descriptive analysis

Descriptive statistics (mean, standard deviation, minimum and maximum) were calculated for pre and post test scores of both groups.

2) Prerequisite tests

Data normality was tested using Shapiro-Wilk and Kolmogorov-Smirnov tests. Homogeneity of variance was assessed using Levene's test.

3) Hypothesis testing

The following hypotheses were tested:

H_1 (within-group, experimental): There is a significant difference in students' digital literacy before and after engaging with the PBL-VR model. Tested using Wilcoxon Signed-Rank Test.

H_2 (within-group, experimental): There is a significant difference in students' science comprehension before and after engaging with the PBL-VR model. Tested using Wilcoxon Signed Rank Test.

H_3 (within-group, control): There is a significant difference in students' digital literacy before and after conventional instruction. Tested using Wilcoxon Signed-Rank Test.

H_4 (within-group, control): There is a significant difference in students' science comprehension before and after conventional instruction. Tested using Wilcoxon Signed-Rank Test.

H_5 (between-group): There is a significant difference in post-test scores of digital literacy between the experimental and control groups. Tested using Mann-Whitney U Test.

H_6 (between-group): There is a significant difference in post-test scores of science comprehension between the experimental and control groups. Tested using Mann-Whitney U Test.

4) Effect size calculation

Effect size r was computed through $r = Z/\sqrt{N}$ with interpretation: small ($r < 0.3$), medium ($0.3 \leq r < 0.5$) and large ($r \geq 0.5$) [73]. Significance level was set at $p < 0.05$ for all tests.

5) Cluster-level sensitivity analysis

Given that assignment occurred at the school level (six schools, three per condition) a sensitivity analysis was conducted using school-level aggregated means to verify that the pattern of results held at the cluster level.

F. Ethical Considerations

Research involving human beings was conducted in accordance with established ethical standards. Written informed consent was obtained from the parents, or guardian of all pupils and oral assent from students. All participants were informed that they could withdraw from the study at any time without explanation.

Special cautions were given concerning the use of VR with children. VR exposure was limited to 15 min sequences with pauses to avoid discomfort or motion sickness. Participants were also closely observed for any uncomfortable experience during VR intervention. All information was anonymized and kept confidential per institutional guidelines regarding data protection. At the end of the study, control group participants could go through VR learning materials to establish that all had equal access to the educational intervention.

IV. Result and Discussion

The experimental and control group students were tested with the post-test for determining their digital literacy and structural knowledge related to the human digestion system, conducted following a four-week intervention period. Pre- and post-test scores were compared between the two groups following the procedures described below.

A. Results

1) Analysis of instrument validity and reliability

The two assessment tools were reviewed by a group of specialists in scientific education and educational evaluation. Their evaluation was based on four criteria: (1) item-indicator alignment; (2) fifth grader comprehension; (3) correct Bahasa Indonesian spelling and grammar; and (4) conceptual correctness. Following expert validation, both instruments were pilot-tested with 32 fifth-grade elementary school students from a school in Semarang City that was not included in the main study.

17 multiple-choice questions were developed to test digital literacy. Table 6 presents the item validity results for the digital literacy test. All items demonstrated r_{xy} values greater than the r_{table} value of 0.349 at a significance level of 0.05 (n = 32), confirming that all items are valid. The Cronbach's alpha coefficient was 0.861, indicating high reliability.

Table 6. Digital literacy test's item validity

Item	r_{xy}	r_{table}	Criteria
1	0.548	0.349	Valid
2	0.461	0.349	Valid
3	0.549	0.349	Valid
4	0.468	0.349	Valid
5	0.669	0.349	Valid
6	0.376	0.349	Valid
7	0.658	0.349	Valid
8	0.445	0.349	Valid
9	0.635	0.349	Valid
10	0.583	-	Valid
11	0.614	-	Valid
12	0.467	-	Valid
13	0.578	-	Valid
14	0.629	-	Valid
15	0.594	-	Valid
16	0.534	-	Valid
17	0.561	-	Valid

Note: Cronbach's α = 0.861

Similarly, the science comprehension test on the Human Digestive System consisted of 15 multiple-choice questions. Table 7 presents the item validity results. All 15 items demonstrated r_{xy} values exceeding the r_{table} value of 0.349, confirming their validity. The Cronbach's alpha coefficient was 0.872, which was indicative of a high value reliability.

Table 7. Item validity of science comprehension test (human digestive system)

Item	r_{xy}	r_{table}	Criteria
1	0.563	0.349	Valid
2	0.617	0.349	Valid
3	0.689	0.349	Valid
4	0.585	0.349	Valid
5	0.595	0.349	Valid
6	0.596	0.349	Valid
7	0.570	0.349	Valid
8	0.716	0.349	Valid
9	0.698	-	Valid
10	0.582	-	Valid
11	0.708	-	Valid
12	0.499	-	Valid
13	0.474	-	Valid
14	0.527	-	Valid
15	0.489	-	Valid

Note: Cronbach's α = 0.872

2) *Descriptive analysis*

Mean pre-test and post-test scores of two group students were compared using descriptive statistics. Table 8 presents the descriptive analysis results for literacy of digital and science understanding on the Human Digestive System.

Similarly, for science comprehension on the Human Digestive System, the experimental group had an average score of M = 82.18 (SD = 8.672) with a mean gain of 17.62 points, while that in pre-test was quite lower at M = 64.56 (SD = 8.943). The post-test score of the control group (M = 73.12, SD = 15.327) was higher than the pretest score (M = 65.29, SD = 12.584) with a mean gain of 7.83 points. This pattern indicates a larger change over time in the experimental group than in the control group for both dependent measures.

Table 8. Descriptive analysis of digital literacy and science comprehension

Variable	Groups	N	Mean	SD	Gain
Digital Literacy	Pretest Experimental	68	69.85	10.892	**13.77**
	Posttest Experimental		83.62	9.754	
	Pretest Control	68	68.91	11.456	3.44
	Posttest Control		72.35	10.127	
Science Comprehension (Human Digestive System)	Pretest Experimental	68	64.56	8.943	**17.62**
	Posttest Experimental		82.18	8.672	
	Pretest Control	68	65.29	12.584	7.83
	Posttest Control		73.12	15.327	

Table 8 indicated that the mean post-test score in digital literacy for the experiment group (M = 83.62, SD = 9.754) was significantly higher than pre-test score (M = 69.85, SD = 10.892), with an average increase of 13.77 points. The control group also increased from pre- (M = 68.91, SD = 11.456) to post-test scores (M = 72.35, SD = 10.127), with a smaller mean gain of 3.44 points in the final test score than that of the experimental group. The comparison of mean gain scores is presented in Fig. 3.

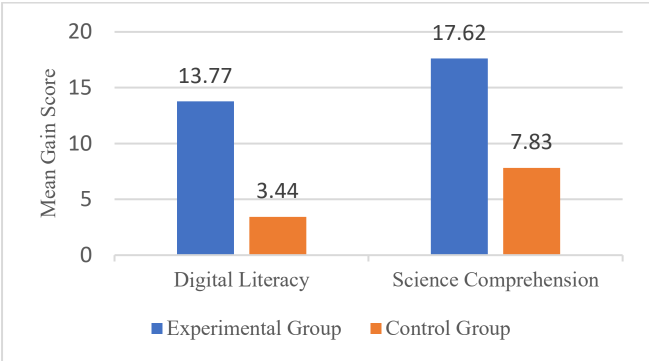

Fig. 3. Comparison of mean gain scores between experimental and control groups on digital literacy and science comprehension.

According to the minimum competency criterion (*Kriteria Ketuntasan Minimal*/KKM) of 75 post-test scores, descriptive differences were observed between groups. For digital literacy, 52 students (76.5%) in the experimental group received scores ≥75, compared to 30 students (44.1%) in the control group. For science comprehension (Human Digestive System), 50 students (73.5%) in the experimental group achieved scores ≥75, compared to 36 students (52.9%) in the control group. These descriptive patterns suggest a higher proportion of students in the experimental group met the minimum competency threshold.

3) *Prerequisite tests*

a) *Normality test*

The Kolmogorov-Smirnov and Shapiro-Wilk tests were conducted to assess the normality of data distribution. Data is considered normally distributed if the significance value exceeds 0.05. The results of the normalcy test for literacy of digital and science understanding revealed that many data distributions deviated from normality (Sig. < 0.05). Consequently, non-parametric statistical tests were selected for subsequent analyses.

b) *Homogeneity test*

Equality of variance in the post test data between experimental and control groups was tested using Levene's test. A value is considered homogeneous if the p-value exceeds 0.05. The output indicated that data of digital literacy post-test were homogenous (Sig. = 0.812 > 0.05) and the science comprehension post-test results indicated heterogeneity (Sig. = 0.003 < 0.05). Considering the non-normal distributions of several distributions, nonparametric statistical tests (Wilcoxon and Mann-Whitney U test) were used for hypothesis testing.

4) Hypothesis testing

a) Wilcoxon signed-rank test

The Wilcoxon Signed-Rank Test was used to evaluate the presence of significant changes between pre-test and post-test scores in the both groups.

Table 9. Wilcoxon signed-rank test results for both groups

Variable	Group	Z	Asymp. Sig. (2-tailed)
Digital Literacy (Post-Pre)	Experimental	–6.482	**< 0.001**
Digital Literacy (Post-Pre)	Control	–2.341	**0.019**
Science Comprehension (Post-Pre)	Experimental	–6.815	**< 0.001**
Science Comprehension (Post-Pre)	Control	–3.892	**< 0.001**

Note: Based on negative ranks.

Both groups showed significant pre-to-post improvements. However, the magnitude of Z values was substantially larger for the experimental group, indicating greater improvement. Regarding digital literacy, as also reported in Table 9, the Wilcoxon test yielded Z = –6.482 (Asymp. Sig. (2-tailed) < 0.001). This finding supports H1, suggesting that the PBL-VR model may have contributed to enhancing digital literacy. Similarly, the Wilcoxon test for science comprehension yielded Z = –6.815 (Asymp. Sig. (2-tailed) < 0.001), therefore H2 is also supported. These results suggest that students' comprehension of the Human Digestive System improved after engaging with the PBL-VR model.

b) Mann-Whitney U test

To determine if the PBL-VR model yielded substantially different results than standard training, the post-test scores of the experimental and control groups were compared using the Mann-Whitney U test.

The Mann-Whitney U test findings are indicated in Table 10. U = 1124.500, Z = –4.923 and Asymp. Sig. (2-tailed) < 0.001, with a medium effect size of r = 0.42. For science comprehension, U = 1487.000, Z = –3.156, and Asymp. Sig. (2-tailed) = 0.002 < 0.05, with small-to-medium effect size of r = 0.27. These results suggest that the experimental group performed better than the control group in both digital literacy and science comprehension.

Table 10. Mann-Whitney U test results comparing experimental and control groups

Statistic	Digital Literacy	Science Comprehension
Mann-Whitney U	1124.500	1487.000
Wilcoxon W	3470.500	3833.000
Z	–4.923	–3.156
Asymp. Sig. (2-tailed)	**< 0.001**	**0.002**
Effect Size (r)	**0.42 (Medium)**	**0.27 (Small-Medium)**

c) Cluster-level sensitivity analysis

Given that the six schools were the units of assignment, a sensitivity analysis was conducted comparing school-level aggregated mean gains. The three experimental schools showed mean gains of 12.8, 14.1, and 14.4 for digital literacy and 16.9, 17.8, and 18.2 for science comprehension. The three control schools showed gains of 2.9, 3.5, and 3.9 for digital literacy and 7.1, 8.0, and 8.4 for science comprehension. While the small number of clusters (n = 6) precludes formal statistical testing at the school level, the consistent pattern across all schools, with every experimental school outperforming every control school on both measures, provides supporting evidence that the group differences are not driven by a single outlier school.

B. Discussion

The findings of this study suggest that PBL-VR instructional package is associated with greater gains in both digital literacy and science comprehension compared to conventional instruction among fifth-grade students. It should be noted that this study compared an active, technology-enhanced learning approach (PBL-VR) with a teacher-directed conventional learning model that did not incorporate any digital resources. Given this design, the observed differences reflect the combined effect of the PBL pedagogical approach and VR technology together, and it is not possible to isolate the independent contribution of either component. The magnitude of difference in learning gains consistent with extensive prior research demonstrating that active learning approaches are associated with better outcomes than passive instruction [74–76].

The differential effects observed between digital literacy (r = 0.42, medium effect) and science comprehension (r = 0.27, small-to-medium effect) can be understood through the lens of Cognitive Load Theory and Multimedia Learning Theory. For digital literacy, the PBL-VR intervention provided direct, hands-on experience with digital tools (students operated VR headsets, navigated virtual environments, and engaged with digital interfaces) thereby reducing the gap between learning about digital technology and actually using it. This alignment between learning activities and assessment content (knowledge about digital concepts and tools) likely contributed to lower extraneous cognitive load and higher germane load for digital literacy outcomes.

In contrast, science comprehension involves more complex conceptual restructuring. While VR visualization of the digestive system may have supported initial encoding of anatomical information through the visual-spatial channel (consistent with Mayer's CTML), deeper understanding of processes such as enzymatic digestion and nutrient absorption requires extended cognitive processing and schema construction that may not be fully achieved within the intervention period. The higher intrinsic cognitive load associated with abstract biological processes [65] may have limited the extent to which VR visualization alone could produce large gains in science comprehension. This interpretation aligns with CLT's prediction that complex material with high intrinsic load is more resistant to instructional interventions [64].

The five stages of PBL (problem orientation, organizing for study, investigation, developing artifacts, and analysis/evaluation) provided a structured framework that guided students through increasingly complex cognitive tasks [51]. In this study, presenting children with real-world problems related to digestion, such as the scenario about unhealthy eating habits, engaged students' interest and motivated them to apply their VR-based observation to meaningful contexts.

The use of Virtual Reality technology as part of the PBL framework provided semi-immersive 3D visualization of The Human Digestive System that conventional approach could not offer [54]. While the smartphone-based VR headsets have more limited immersive capability compared with high-end VR systems, they provided sufficient depth perception and interactivity for students to observe organ structures and digestion processes. This semi-immersive experience addressed a core challenge in science education, namely the difficulty of teaching abstract internal biological processes that students cannot directly observe [12, 13].

The gains in digital literacy (mean difference 13.77 for experimental vs. 3.44 for control) are associated with the hands-on technology engagement during the intervention. Students in the experimental group operated VR headsets, navigated virtual environments, and engaged with digital materials throughout the learning process. The active technology engagement may have cultivated knowledge about digital literacy concepts within learning context rather than through isolated technology instruction [3]. However, it is important to acknowledge that the digital literacy assessment used in this study was knowledge-based (measuring understanding of digital concepts, terminology, and procedures) rather than performance-based. Therefore, while the results indicate improved knowledge of digital literacy concepts, claims about transfer to actual digital skills should be interpreted with caution. Future studies incorporating performance-based assessments (e.g. observed task completion in digital environments) would be needed to verify skill transfer.

The improvement in science comprehension (mean gain of 17.62 points in the experimental group vs. 7.83 in the control group) suggests that the combined PBL-VR approach may be associated with enhanced conceptual understanding. The VR experience likely created visual representations that supported students' memory of digestive organs and process, while the subsequent PBL activities allowed students to apply, interpret, and consolidate this information through cooperative inquiry and problem-solving [18, 77]. Research has suggested that multimodal learning approaches involving visual and cognitive processing may increase depth of understanding and retention of scientific concepts [78, 79].

An important consideration in interpreting these findings is the potential novelty effect. Given that the majority of students (82.4% in the experimental group) had no prior VR experience, the initial excitement associated with VR technology may have contributed to engagement and, consequently, learning outcomes. However, several factors suggest that the observed gains are not solely attributable to novelty. First, the digital literacy improvements (mean gain of 13.77 points) reflect knowledge gains in specific content domains (hardware concepts, software functionality, internet safety) that require actual learning rather than mere excitement. Second, the intervention spanned four weeks with eight sessions, providing sufficient time for initial novelty effects to diminish. Third, the improvement was consistent across both dependent variables and across all three experimental schools. Nevertheless, the extent to which novelty contributed to the observed effects cannot be definitively determined without a longer-term follow-up or a comparison with a PBL-only condition, and longitudinal studies are needed to assess whether these gains are sustained over time.

The results of this study are consistent with other studies on technology-enriched PBL. The prior research shows that combining multiple technologies with PBL enhances student learning in various levels and disciplines [18, 21, 30]. However, this study offers a potentially distinctive contribution for three respects: (1) demonstrating that low-cost, smartphone-based VR technology may effectively support science learning in resource-constrained settings; (2) addressing misconceptions about internal biological processes through visual immersion; and (3) suggesting that technology-enhanced PBL may simultaneously improve digital literacy knowledge and science comprehension. The medium (r = 0.42) and small-to-medium (r = 0.27) effect sizes for digital literacy and science comprehension, respectively, indicate meaningful differences between groups that may support the potential utility of PBL-VR as a cost-effective model to facilitate elementary science learning in resource-deprived settings.

The smaller standard deviation in the experimental group's post-test scores of science comprehension (SD = 8.672) compared to the control group's (SD = 15.327) suggests that PBL-VR model may have been beneficial for students across initial ability levels [48, 49]. VR visualization and collaborative problem-solving may have provided multiple pathways to understanding, potentially accommodating diverse learning styles [60, 80].

In spite of the promising results, some limitations of this study need to be addressed. First, the sample is limited to fifth-grade students in Semarang City, which may limit generalizability to other grades and regions, or educational contexts. Second, and critically, assignment was randomized at the school level with only six schools (three per condition). Statistical analyses were conducted at the individual student level, which may overestimate significance by not fully accounting for the clustered nature of the data. Although the sensitivity analysis at the school level showed consistent patterns, the small number of clusters limits the statistical power of cluster-level analyses. Readers should interpret the reported p-values with appropriate caution. Third, the study compared the complete PBL-VR package against conventional instruction; without a PBL-only or VR-only comparison group, the independent contributions of PBL and VR cannot be disentangled. Fourth, the study was limited to the Human Digestive System and it is unknown whether findings generalize to other science topics. Fifth, the 4-week intervention may not be sufficient to observe long-term retention of knowledge and skills; no retention tests were administered. Sixth, potential confounding factors such as teacher enthusiasm and implementation fidelity may have influenced results. Seventh, the digital literacy assessment measured knowledge and understanding rather than performance-based skills, limiting the strength of skill-transfer interpretations.

The present study has implications for educational practice, policy, and research. The PBL-VR model offers teachers a structured approach for introducing accessible semi-immersive technology into elementary science education. The use of low-cost smartphone-based VR headsets (US$ 5–15 per unit) suggests that technology-supported learning may be accessible even for schools with limited resources. For policymakers in developing countries, the results encourage strategic investment in cost-effective educational technologies that can scale across under-resourced schools. For researchers, the study highlights opportunities to explore PBL-VR applications across different subjects, grade levels, and cultural contexts; as well as the underlying cognitive processes through which semi-immersive VR may support science learning.

V. Conclusion

This research provides empirical evidence suggesting that a Problem-Based Learning model integrated with low-cost Virtual Reality (PBL-VR) may effectively support the enhancement of digital literacy and science comprehension among elementary school students. The study's findings contribute to constructivist learning theory by demonstrating how the sequential design of VR exploration followed by PBL activities can create authentic learning environments that align with both Cognitive Load Theory principles (managing intrinsic, extraneous, and germane load through temporal sequencing) and Mayer's Cognitive Theory of Multimedia Learning (leveraging dual-channel processing multimodal instruction).

A key practical contribution of this study is the evidence that affordable, smartphone-based VR solutions (such as Google Cardboard) can be implemented in resource-constrained educational settings with meaningful educational outcomes. This challenges the perception that effective VR integration requires expensive hardware, and has important implications for educational equity in developing countries. The PBL-VR model offers a scalable, cost-effective approach that can be incorporated into science curricula, providing a pathway for broader technology adoption in under-resourced schools.

Future research should pursue several directions: (1) longitudinal studies to assess whether the gains in digital literacy and science comprehension are retained over time; (2) comparative designs including PBL-only and VR-only conditions to isolate the contributions of each component; (3) extension to different science topics, grade levels, and cultural contexts to establish generalizability; (4) integration of performance-based digital literacy assessments to move beyond knowledge-level measurement; (5) examination of cognitive load measures during VR-PBL instruction to empirically validate the theoretical framework proposed here; and (6) investigation of how the PBL-VR model can be combined with other pedagogical approaches such as flipped learning or gamification.

Appendix

Table A1. Digital literacy assessment: full instrument with scoring key, indicator mapping, and DigComp 2.2 alignment

No	Indicator	Item & Options	Key	Score	DigComp 2.2 Area
1	Understanding of terminology, functionalities, and categories of hardware	**Which of the following is an example of computer hardware?** a) Microsoft Word b) Google Chrome c) Keyboard d) Wi-Fi	**C**	1	1. Information and Data Literacy (1.1)
2	(continued)	**What is the main function of a hard disk?** a) Storing data b) Displaying visual output c) Connecting to the internet d) Processing calculations	**A**	1	1. Information and Data Literacy (1.1)
3	(continued)	**Which device is used to give instructions to the computer by typing?** a) Mouse b) Printer c) Keyboard d) Speaker	**C**	1	1. Information and Data Literacy (1.1)
4	Understanding of terminology, functionalities, and categories of software	**Which of the following is an example of application software?** a) RAM b) Processor c) Hard disk d) Microsoft Excel	D	1	1. Information and Data Literacy (1.1)
5	(continued)	**What type of software controls the basic operations of a computer?** a) Application software b) Operating system c) Browser d) Antivirus	**B**	1	1. Information and Data Literacy (1.1)
6	(continued)	**Which software is commonly used to create presentations?** a) Microsoft Excel b) Microsoft Word c) Microsoft PowerPoint d) Notepad	**C**	1	1. Information and Data Literacy (1.1)
7	Understanding of terminology, functionalities, and categories of VR tools and applications	**What does Virtual Reality (VR) allow users to do?** a) Print documents faster b) Experience a computer-generated 3D environment c) Send emails automatically d) Edit photos	**B**	1	5. Problem Solving (5.4)
8	(continued)	**Which device is needed to view Virtual Reality content on a smartphone?** a) Google Cardboard b) Printer c) Projector d) Scanner	**A**	1	5. Problem Solving (5.4)
9	(continued)	**What is a key feature of a VR learning application?** a) It shows 3D by scanning QR b) It provides interactive 3D environments c) It replaces the teacher d) It works without any device	**B**	1	5. Problem Solving (5.4)
10	Understanding various browser types and strategies for optimum browser utilization	**Which of the following is a web browser?** a) Microsoft Word b) Photoshop c) Windows d) Google Chrome	**D**	1	1. Information and Data Literacy (1.1)
11	(continued)	**What should you do to find specific information efficiently using a browser?** a) Type random words b) Use specific keywords c) Open multiple tabs without purpose d) Avoid using search engines	**B**	1	1. Information and Data Literacy (1.1)
12	Understanding several methods for obtaining information online	**Which is the most reliable way to find accurate information online?** a) Using verified educational websites b) Believing any social media post c) Clicking on the first result only d) Asking random strangers online	**A**	1	1. Information and Data Literacy (1.2)
13	Understanding the procedures for doing online information searches	**What is the correct first step when searching for information online?** a) Click on advertisements b) Identify what information you need c) Download every file you find d) Share your password	**B**	1	1. Information and Data Literacy (1.1)
14	Understanding security in the utilization of the internet and immersive technologies	**What should you do to protect your personal information online?** a) Share your password with friends b) Use strong and unique passwords c) Use the same password for all accounts d) Post your home address online	**B**	1	4. Safety (4.1, 4.2)

15	Understanding etiquette of online communication	**Which behavior shows good etiquette when communicating online?** a) Writing in all capital letters b) Sharing other people's photos without permission c) Sending spam messages d) Being polite and respectful	**D**	1	2. Communication and Collaboration (2.5)
16	Understanding ways to save and manage online information	**What is an effective way to save important information found online?** a) Memorize everything b) Ignore it and search again later c) Take a photo of the screen with another phone d) Bookmark the webpage or save the file	**D**	1	1. Information and Data Literacy (1.3)
17	Understanding appropriate and inappropriate online content	**Which of the following is an example of inappropriate online behavior?** a) Reading educational articles b) Watching learning videos c) Bullying someone in a chat group d) Doing homework using online resources	**C**	1	4. Safety (4.3)
		TOTAL SCORE		**17**	

Notes:
• Scoring formula: Final Score = (Total Correct / 17) × 100
• Items were originally administered in Bahasa Indonesia. English translations are provided here for international readership.
• DigComp 2.2 areas: 1 = Information and Data Literacy; 2 = Communication and Collaboration; 4 = Safety; 5 = Problem Solving.
• Sub-competences: 1.1 = Browsing, searching, and filtering; 1.2 = Evaluating data and information; 1.3 = Managing data and information; 2.5 = Netiquette; 4.1 = Protecting devices; 4.2 = Protecting personal data; 4.3 = Protecting health and well-being; 5.4 = Identifying digital competence gaps.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N.S. conceptualized the study, conducted data collection and analysis, and drafted the manuscript. S.S. supervised research design and provided critical revision. S.P.K. contributed to theoretical framework and manuscript revision. All authors approved the final manuscript.

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