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Digital Pedagogical Model Based on Climate Change Issues Integrated with Virtual Reality Technology to Enhance Students' Critical Thinking and Climate Change Awareness

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Abstract

Climate change education is crucial for equipping students to tackle pressing global challenges, yet traditional methods often fail to foster critical thinking (CT) and awareness. This study aimed to develop a digital pedagogical model based on climate change issues integrated with Virtual Reality (VR) technology to enhance students' CT and climate change awareness. The research employed a Research and Development (R&D) approach, involving validation, practicality testing, and effectiveness evaluation. Validity data were obtained through expert validation (involving five validators), while practicality and effectiveness data were gathered through implementation processes involving two observers (evaluating model practicality) and 38 high school students (effectiveness test subjects). Implementation utilized a pretest-posttest design and was analyzed descriptively and quantitatively. The findings indicate that the model is valid, with an average validation score of 4.15, and practical, with an implementation score of 4.80 categorized as "very good." The effectiveness test showed significant improvements in students' CT skills, with the average score increasing from the "less critical" to the "moderately critical" category, and in climate change awareness, which rose from the "moderate" to the "high" category. These results highlight the effectiveness of integrating PBL with VR technology in enhancing students' CT skills and awareness. This study contributes to advancing technology-based education and emphasizes the importance of adopting immersive, problem-based pedagogies in tackling global issues like climate change.

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INTRODUCTION

Recognizing the critical importance of climate change and its implications for the sustainability of human life, educational institutions worldwide have integrated this issue into their curricula (Bleazby et al., 2023; Eilam, 2022). In Indonesia, climate change education is incorporated into the *"Kurikulum Merdeka"* (Independent Curriculum) at Phase E (Grade X). The aim of teaching climate change in educational institutions is to cultivate a generation of learners equipped with critical thinking skills to understand and address climate change (Young et al., 2023). However, traditional teaching methods that rely heavily on information delivery have proven insufficient in fostering students' critical thinking and awareness regarding this issue (Hillary et al., 2023). Previous studies also highlight that little is known about how secondary school curricula address students' learning needs in climate change education (Eilam et al., 2020).

Recent studies indicate that students' critical thinking skills and scientific attitudes remain at low levels when climate change education is conducted using traditional methods (Pursitasari et al., 2023). To validate this issue, a research team conducted an assessment of students' critical thinking skills on climate change content and interviewed science teachers at a secondary school in Mataram City in November 2023. The results revealed that students' critical thinking skills regarding climate change were categorized as low. Interviews with teachers further revealed their limited understanding of innovative pedagogies for teaching climate change. Critical thinking is essential in climate change education, as it enables learners to holistically evaluate mitigation and adaptation solutions while enhancing their capacity for action (Oberman & Sainz, 2021). Therefore, educational institutions are expected to produce graduates capable of driving systemic changes to combat climate change, beginning with the integration of knowledge and critical thinking skills into learning processes (Vaughter, 2016).

Another challenge in fostering critical thinking for climate change education is the increasing trend of online learning, which further underscores the need for an adequate pedagogical system (Newsome et al., 2023). In online learning environments, the risk of hindering students' critical thinking development is greater. Information transmission through online platforms alone does not effectively stimulate the deep engagement necessary for nurturing robust critical thinking skills (Sollied-Madsen et al., 2021). Students require experiential learning opportunities that allow them to explore the realities of climate change, promoting active participation and critical exploration (Minan et al., 2021).

Addressing the challenges in enhancing students' critical thinking and awareness of climate change requires initiatives to develop a more dynamic, innovative, and engaging pedagogical infrastructure. This infrastructure should emphasize authentic learning contexts that visualize environmental conditions caused by climate change. This aligns with previous studies recommending innovative educational strategies to effectively teach climate change (Monroe et al., 2019). Authentic learning is closely associated with problem-based pedagogy, which emphasizes exploration of real-world problems—a principle reflected in problem-based learning (PBL) (K. Smith et al., 2022). While climate change impacts, such as global warming, are authentic issues, they are often abstract and not directly observable. Therefore, climate change education cannot rely solely on online learning; visualization technologies, such as virtual reality, are needed within digital learning platforms to effectively teach this topic. The challenges in climate change education justify the need to develop an innovative pedagogical model to enhance students' critical thinking and awareness regarding climate change issues.

Framework for Problem-Solving

A new initiative is proposed as a problem-solving approach, specifically aimed at enhancing students' critical thinking and awareness of climate change issues. This approach involves developing a digital pedagogical model infrastructure that integrates problem-based learning (PBL) with virtual reality (VR) technology. The foundation of this model is supported by three key aspects. First, digital pedagogy is designed to address inclusive learning needs, enabling students to engage in deep thinking processes. This aligns with the advancement of digital technology, where it is projected that by 2025, digital learning will be widely adopted across the globe (Palvia et al., 2018). Thus, the pedagogical infrastructure must be built with a digital system to ensure adaptability and accessibility in modern educational settings (Herodotou et al., 2020). Second, climate change is a global, authentic problem, and PBL is the most appropriate pedagogy to serve as a bridge for teaching this issue. Authentic content aligns with pedagogical methods that emphasize exploration of real-world problems, as seen in PBL frameworks (K. Smith et al., 2022; Suryati et al., 2021). Through this method, students are encouraged to investigate, collaborate, and critically reflect on realistic scenarios that represent the complexities of climate change.

The third aspect focuses on the immersive capabilities of VR technology, which allows students to experience firsthand the impacts of climate change through simulated real-world scenarios. By integrating VR into the pedagogical model, students are transported to various environments where they can observe and analyze the tangible consequences of climate change, fostering both critical thinking and emotional engagement (Meijers et al., 2023). The integration of these supporting resources—PBL, digital pedagogy, and VR technology—forms the basis of a dynamic and innovative infrastructure. This infrastructure is designed to facilitate authentic and engaging learning experiences, enabling students to deeply explore climate change issues and develop critical awareness of potential mitigation and adaptation strategies. The combination of PBL and VR technology offers a holistic learning experience that not only enhances students' critical thinking skills but also fosters a heightened sense of awareness and responsibility toward addressing climate change.

Research Objectives and Novelty

This research aims to develop a digital pedagogical model based on climate change issues integrated with VR technology that is valid, practical, and effective in enhancing students' critical thinking and awareness of climate change issues. The model focuses on providing an innovative, immersive learning experience where students can explore real-world scenarios of climate change impacts, enabling them to critically analyze and evaluate solutions.

The novelty of this research lies in the integration of VR technology into a problem-based digital pedagogy model specifically tailored for climate change education. While previous studies have explored the benefits of PBL or VR independently, this study combines both approaches to create a holistic, immersive learning environment. This integrated model not only addresses the limitations of traditional teaching methods but also aligns with the growing trend of digital learning to provide a more dynamic and authentic educational experience. The development of this model contributes to filling a significant gap in climate change education by equipping students with critical thinking skills and heightened awareness, empowering them to become active participants in mitigating and adapting to climate change challenges.

LITERATURE REVIEW

Problem-based Learning

Problem-Based Learning (PBL) has gained significant recognition in science education as an effective method to promote active learning and improve students' academic achievement, attitudes, and conceptual understanding (Akınoğlu & Tandoğan, 2007). PBL aligns well with the goals of science education by fostering problem-based reasoning skills and mirroring real-world practices, thereby enhancing contextual learning of fundamental scientific concepts (Rendas et al., 2006). This approach emphasizes authentic learning situations over artificial ones, encouraging a deeper understanding of scientific concepts (Mayer, 2008). By integrating PBL into science education, students engage in knowledge construction while solving theoretical problems that reflect real-world challenges (Barak, 2020).

Research has shown that PBL naturally facilitates the development of scientific concepts, interdisciplinary approaches, and unique research-based learning experiences, harmonizing content and process in science education (Han, 2017). PBL encourages students to ask questions, refine problems, analyze data, build models, and refine explanations, fostering a comprehensive understanding of the world around them (Tapilouw et al., 2017). Moreover, the integration of PBL in STEM education has been shown to improve students' environmental literacy, demonstrating its effectiveness in enhancing scientific and information literacy among elementary education learners (Widowati et al., 2021). The implementation of PBL in science education has been associated with various positive outcomes, including enhanced critical thinking skills, improved learning outcomes, and greater student engagement compared to traditional teaching methods (Setyono et al., 2018).

PBL not only focuses on problem-solving skills but also emphasizes independent learning, teamwork, and knowledge retention, contributing to a more holistic educational experience (Shi et al., 2000). By incorporating PBL into the curriculum, students encounter unstructured problems that guide their learning agenda, fostering essential goals such as conceptual learning, student-designed experiments, and the development of scientific reasoning skills. Furthermore, PBL enriches classroom learning experiences by providing opportunities for students to apply scientific knowledge, engage in inquiry-based learning, and develop mathematical reasoning skills for decision-making processes (Toto, 2022).

Integrating PBL with technology-based tools and multimedia resources can further enhance science education, aligning it with the demands of advanced technological learning environments (Yuan et al., 2022). Studies have also highlighted the integration of PBL with character education values, contributing to holistic student development by fostering not only academic growth but also ethical and moral values (Estuhono & Afriko, 2018).

In conclusion, PBL has emerged as a valuable approach in science education, offering a student-centered exploration method that enhances critical thinking, problem-solving skills, and knowledge retention. By integrating PBL into science education, educators can create authentic learning experiences that reflect real-world challenges, promote interdisciplinary learning, and foster a deeper understanding of scientific concepts. The evidence-based principles of PBL align with the goals of science education, emphasizing active learning, reasoning skill development, and contextual understanding of fundamental scientific knowledge.

Climate Change Issues

Climate change education is a critical component of science education, supported by numerous studies that emphasize the need to incorporate climate change topics into curricula to enhance students' understanding and engagement with this global issue. Carman et al. (2021) highlight the importance of connecting climate change to students' daily lives and empowering them to take action, which can significantly improve their knowledge of climate change. Similarly, Sharma (2012) advocates for placing climate change at the center of science education, underscoring the necessity of addressing this topic comprehensively within educational frameworks. This perspective reflects a consensus among researchers regarding the pivotal role of climate change education in shaping students' awareness and knowledge of environmental challenges.

Previous studies have explored the potential of climate change education to promote interdisciplinary and transdisciplinary approaches in science curricula, emphasizing the integration of diverse perspectives and disciplines to enrich students' understanding of climate change (Asante et al., 2024). Ramadani et al. (2023) outline the importance of connecting climate change education with broader social implications, highlighting the interconnectedness between climate systems and various aspects of human society. This approach equips learners with the skills necessary for both mitigation and adaptation strategies. These insights underscore the multifaceted nature of climate change education, stressing the need for a holistic framework that addresses scientific, social, and environmental dimensions of the issue.

Watts (2019) emphasizes the value of teaching climate change in a manner that promotes critical thinking and scientific inquiry, aiming to provide students with the skills required to understand climate change beyond ideological and partisan biases. Teaching climate change concepts demands structured efforts from educators to integrate these topics effectively into educational programs and learning processes (Eze et al., 2022). These studies highlight the crucial role of educators in delivering high-quality climate change education and the need to empower teachers with the knowledge and resources necessary to effectively engage students with this complex subject.

Ferguson and White (2023) address the aesthetic dimensions of climate change education, emphasizing the role of formal educational institutions, particularly schools, in fostering an appreciation of climate knowledge and empowering individuals to advocate for a sustainable future. Other studies emphasize the importance of leveraging technology and innovative tools to improve students' understanding of the challenges and solutions associated with climate change (Asimakopoulou et al., 2021). This perspective underscores the variety of approaches and strategies that can be applied to enrich climate change education and inspire meaningful actions among students.

A comprehensive approach to climate change education is needed, one that advocates for students to understand, communicate, and make informed decisions about climate change from a multidisciplinary perspective (Duram, 2021; Shwom et al., 2017). These studies collectively emphasize the importance of critical thinking as a central component of climate change education, as noted by Young et al. (2023).

Virtual Reality

Virtual Reality (VR) has emerged as a powerful tool in science education, offering immersive and interactive experiences that have the potential to revolutionize traditional teaching methods (Au & Lee, 2017). By creating virtual environments, VR enables students to directly engage with complex scientific concepts, making learning more experiential, engaging, and meaningful (Ayoub & Pulijala, 2019). In the field of education, VR technology has paved the way for innovative teaching and learning processes, providing unique methods to support and enhance educational outcomes (Wang et al., 2022).

The use of VR in science education has been widely recognized as a promising practice, with research indicating its ability to increase student interest and engagement (Zhang & Bowman, 2022). Comprehensive reviews on VR applications in educational institutions have highlighted its diverse integration into teaching and learning processes (Al Farsi et al., 2021). The continuous development of VR applications across various fields of education demonstrates its significant impact on educational outcomes, particularly in enhancing the learning experience (Lie et al., 2022). Several studies have confirmed the effectiveness of VR in promoting better educational results by creating interactive and immersive environments that engage students deeply with scientific content (Ding & Li, 2022; Moussa et al., 2022).

Research has shown that VR's ability to provide interactive and immersive learning environments can significantly influence science education. Students' perceptions of VR applications in science classes are overwhelmingly positive, as they find VR-based learning environments more engaging and enjoyable compared to traditional teaching methods (Urhan & Akpinar, 2024). The use of VR in science education transcends the boundaries of traditional classrooms, enabling its application in specialized fields such as environmental education. In these contexts, VR and augmented reality (AR) technologies have been integrated to create immersive and interactive learning experiences that allow students to explore and interact with environmental issues, such as climate change, in realistic virtual settings (Barnett & Pua, 2020; Dalanon, 2023; Maipas et al., 2021).

Overall, the integration of VR technology into science education has the potential to transform the way students learn and interact with scientific concepts. By providing immersive, interactive, and experiential learning opportunities, VR not only increases students' interest and engagement but also enhances their understanding of complex scientific topics. As VR technology continues to advance and becomes more accessible, its role in science education is expected to grow significantly, offering new opportunities for innovative teaching and learning practices. VR's ability to create realistic simulations and dynamic environments opens doors for educators to deliver content in ways that are both effective and engaging, ultimately shaping a future of education that is technology-driven, student-centered, and focused on enhancing learning outcomes.

Critical Thinking in Climate Change Education

One of the most prominent contributors to the concept of critical thinking is Robert Ennis. Ennis (2018) defines critical thinking as a reflective and reasoned process aimed at determining what to believe or what actions to take. Critical thinking involves both cognitive abilities and dispositions, which complement each other (Ennis, 2015). Disposition plays a crucial role because the ability to think critically becomes ineffective without the desire and habitual practice of applying it in daily life. The cognitive aspect refers to an individual's capacity to logically and systematically analyze problems, develop evidence-based solutions, and make rational judgments. Disposition, on the other hand, pertains to a person's inclination or attitude toward consistently engaging in critical thinking processes. Without a strong disposition, the cognitive capacity for critical thinking may remain underutilized, as it requires motivation and willingness to engage deeply and critically with problems. Therefore, developing both aspects should be a primary focus in science education to foster learners who are not only skilled at critical thinking but also proactive in applying it to real-world problem-solving (Abrami et al., 2008; Aizikovitsh-Udi & Cheng, 2015; Kinoshita, 2022). Indicators of critical thinking skills used in this research are based on the following six skill indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 2020).

The cultivation of critical, systematic, and creative thinking skills is essential for addressing the challenges of climate change (Hadiapurwa et al., 2024). Integrating critical thinking skills into education, particularly in the context of climate change, is crucial for equipping students with the capacity to analyze, evaluate, and propose solutions to real-world problems (Efwinda et al., 2023). Research has emphasized the importance of fostering critical thinking in students as they engage with climate change issues, enabling them to develop appropriate perspectives and make well-informed decisions (Aliyu et al., 2023). By learning to question assumptions, synthesize information, and examine potential solutions critically, students can become active participants in addressing environmental challenges.

Efforts have been made to develop interactive teaching materials centered on climate change to enhance students' critical thinking skills and foster positive attitudes toward science (Pursitasari et al., 2023). For example, integrating climate change and sustainability concepts into curricula has shown significant potential for developing students' abilities to critically evaluate resource utilization and explore alternative solutions (Cruz et al., 2018). These initiatives align with the goals of STEM education, which emphasize evaluating students' competencies in problem-solving and critical thinking to prepare future professionals capable of addressing global environmental challenges (Powers et al., 2021).

Research focusing on students' critical thinking skills related to climate change has underlined the importance of fostering these abilities at an early stage of education (Afandi et al., 2021). Developing critical thinking in early education equips students with essential skills for understanding complex environmental issues and preparing them for lifelong learning and action. Climate change education, however, is recognized as a significant challenge requiring a multidisciplinary approach to address interconnected issues such as climate change, biodiversity loss, and resource depletion (Lavonen, 2022).

In conclusion, critical thinking is a vital component of climate change education, enabling students to analyze problems systematically, evaluate potential solutions, and make evidence-based decisions. By fostering both the cognitive abilities and the dispositions necessary for critical thinking, educators can prepare learners to confront climate change challenges effectively. Integrating critical thinking skills into science curricula provides students with the tools to become active problem-solvers and responsible decision-makers in addressing environmental issues. As such, a multidisciplinary and well-structured educational approach is essential to nurturing critical thinking skills and empowering students to take meaningful actions for a sustainable future.

Awareness of Climate Change Issues

Student awareness in learning refers to their active understanding and attention toward their learning processes, including goals, strategies, and reflections on what they have learned. It involves how students perceive and comprehend various concepts across disciplines. Previous studies have explored students' levels of awareness in different fields, emphasizing the importance of educators recognizing students' self-conceptions to effectively tailor teaching methods (Yang et al., 2014). Exploring student awareness is critical because it enables educators to adapt instructional strategies that address gaps in understanding and foster deeper engagement (Yang et al., 2014). Prior research has highlighted the importance of student awareness in domains such as sustainability and environmental education (Ablak & YeşiĺLtaş, 2020; Malik et al., 2019). For instance, examining awareness of sustainable technology practices provides insights into students' knowledge and attitudes toward sustainable behavior (Malik et al., 2019). Similarly, evaluating students' awareness of environmental concepts can assist in assessing their understanding of critical environmental issues (Ablak & YeşiĺLtaş, 2020).

Assessing students' awareness of climate change requires a comprehensive approach that draws from research addressing various dimensions of this topic. Akrofi et al. (2019) emphasize that enhancing students' knowledge of climate change is essential for raising societal awareness. Kousar et al. (2022) further highlight the significance of increasing awareness among students as a means of promoting environmental protection. Studies have shown that scenario-based learning significantly enhances students' attitudes and awareness toward climate change (Álvarez-Nieto et al., 2022). Additionally, student participation in climate change-related activities has been found to positively impact their awareness and engagement (Incesu & Yas, 2024). This active involvement exposes students to real-world climate challenges, fostering a sense of responsibility and urgency to act.

The alarming effects of climate change influence students' perceptions and willingness to engage in mitigation efforts (Deshiana et al., 2022). Increasing student awareness about climate change issues, therefore, plays a critical role in shaping their knowledge, attitudes, and proactive behavior. By adopting strategies that promote awareness, such as experiential learning, scenario-based education, and participatory activities, educators can empower students to understand and address climate change challenges, ultimately encouraging them to contribute to sustainable solutions.

METHODS

Research Design

This study employs a Research and Development (R&D) approach to develop a problem-based digital pedagogical model integrated with virtual reality (VR) technology to enhance students' critical thinking skills and climate change awareness. The research adopts the educational R&D framework as outlined by Gall et al. (2014) and adheres to development criteria emphasizing validity, practicality, and effectiveness to achieve the intended goals (Nieveen et al., 2023).

Procedure

The research procedure begins with the planning phase, where the model development process involves defining the objectives, formulating goals, and determining the sequence of instructional activities. This is followed by the development of the preliminary form of the product, during which the digital pedagogical infrastructure (VR technology) is prepared. This phase results in a hypothetical framework for the digital pedagogical model based on climate change issues integrated with VR technology, specifically designed to enhance students' critical thinking skills and awareness of climate change.

Next, the preliminary field testing stage involves validating the model. The pedagogical model undergoes content and construct validation by experts (validators) who evaluate its feasibility and theoretical alignment. Feedback from the validators is incorporated into revisions to refine the model (main product revision). The outcome of this phase is a validated digital pedagogical model based on climate change issues integrated with VR technology.

Following this, the main field testing stage is conducted, where the model is implemented in a simulated environment (Trial-1) involving practitioners (teachers) and observers. The goal is to evaluate the model's practicality—whether it is easy to execute and implement by educators. User feedback from this phase is used to further revise and enhance the model. The revised model is then subjected to operational field testing (Trial-2) in an actual classroom setting to evaluate its practicality and effectiveness. At this stage, a mixed-method approach (quantitative and qualitative) is used, with a pretest-posttest group design to measure the impact of the model on students' critical thinking and awareness. The results are analyzed in alignment with the research objectives.

Participants

The study involves multiple groups of participants, including experts (validators), practitioners (observers), and students (implementation subjects). A total of five validators, who are experienced experts in pedagogical model development and technology integration, are included in the validation process. Two practitioners (teachers) participate as observers to assess the implementation and practicality of the learning process. The study engages 38 high school students from a private school in eastern Indonesia as participants for the implementation phase. Demographically, the students have an average age of 16 years, with a relatively balanced gender distribution between male and female participants.

Permission for conducting the research was obtained from the school where the study was implemented, as well as from the Institutional Review Board at Universitas Pendidikan Mandalika. Ethical research principles were upheld, ensuring the rights, privacy, and informed consent of all participants throughout the research process.

Instruments and Analysis

Validation data were collected using a validation instrument and analyzed using descriptive quantitative and qualitative approaches, as informed by previous studies (Prayogi et al., 2018). The model's practicality was measured based on the implementation of the learning process, assessed using observation sheets. The effectiveness of the model was determined by the improvement in students' critical thinking skills and climate change awareness, as measured from pretest to posttest scores.

Critical thinking data were collected using an essay test, while awareness data were gathered through a questionnaire. The indicators for critical thinking skills followed Facione's framework (2020), which includes interpretation, analysis, evaluation, inference, explanation, and self-regulation. Data on critical thinking skills and climate change awareness were analyzed statistically using JASP software version 0.19.2. Students' critical thinking performance was categorized into levels ranging from "non-critical" to "highly critical" based on prior studies (Prayogi et al., 2018). Similarly, climate change awareness scores were categorized from "low" to "high" to provide a clear understanding of students' pre-intervention and post-intervention conditions.

The results were visualized through descriptive plots, offering a comprehensive representation of students' performance before and after the pedagogical model intervention. These visualizations allow for an in-depth analysis of the model's impact on enhancing critical thinking skills and awareness related to climate change. Through this structured and systematic approach, the study ensures the reliability and validity of the findings while providing clear evidence of the model's practicality and effectiveness in achieving the research objectives.

RESULTS AND DISCUSSION

State of the Art and Conceptual Framework of the Developed Pedagogical Model

Previous research has shown that PBL, climate change context teaching, and digital learning using VR technology have been explored as separate domains. While each of these approaches has demonstrated advantages in enhancing specific aspects of the learning process—such as problem-solving, understanding climate change issues, and leveraging advanced technology—there have been no significant efforts to integrate these three elements into a cohesive digital pedagogical model. PBL has been proven effective in improving students' problem-solving and collaboration skills, while climate change context teaching helps students understand the environmental impact of human activities. On the other hand, VR technology offers a more immersive and interactive learning experience. Unfortunately, the separation of research in these areas has resulted in a limited understanding of how these approaches can complement and reinforce one another.

This study seeks to address this gap by developing a digital pedagogical model infrastructure that integrates PBL, climate change context teaching, and digital learning with VR technology. Through this holistic approach, the aim is to create a learning environment that not only enhances students' critical thinking skills but also raises their awareness of climate change issues. The model leverages the strengths of each component: PBL's ability to encourage active student engagement, climate change teaching's effectiveness in building environmental awareness, and VR technology's capability to provide immersive and realistic learning experiences. The context of previous studies and the novelty of this proposed model are illustrated in greater detail in Figure 1, which provides a visual depiction of how the integration of these three elements can be realized in teaching and learning practices.

Previous research on PBL, which presents authentic problems and promotes investigative problem-solving among students, has demonstrated its effectiveness in enhancing knowledge retention and fostering a deep understanding of concepts (Li & Tsai, 2017). Additionally, PBL has shown positive impacts on students' reasoning performance (Anggraeni et al., 2023). Other studies highlight that exploration and investigation in PBL create opportunities for developing students' critical thinking skills (Calkins et al., 2020). Similarly, the role of technology has been studied in relation to improving scientific process skills, scientific attitudes, and conceptual understanding (Khery et al., 2020), as well as scientific literacy (Khery et al., 2019). In general, technology-based learning environments have been shown to cultivate critical thinking skills (Sönmez, 2021; Suryati, 2017).

Specifically, for VR technology, the literature suggests that VR plays a significant role in enhancing 21st-century skills (Wu et al., 2023). However, its application in the context of climate change education remains underexplored. Other studies note that computer-based educational materials designed for climate change topics can help students learn and increase their interest in climate change knowledge (G. G. Smith et al., 2019). Students require experiential learning ecosystems that enable them to explore the realities of climate change, fostering active participation and critical exploration (Minan et al., 2021).

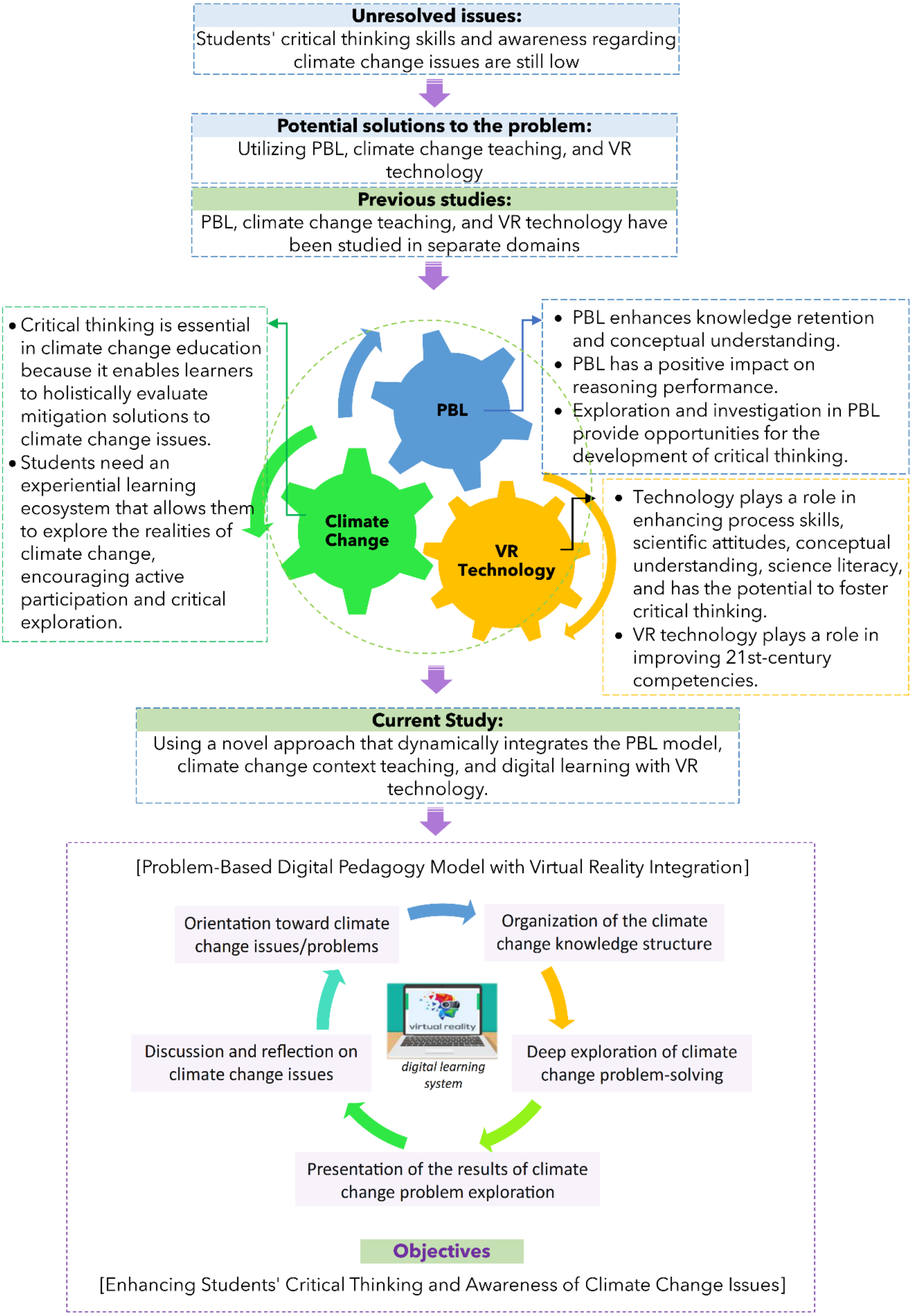

Figure 1. State of the art and conceptual framework of the developed pedagogical model

The current study adopts a novel approach by dynamically integrating PBL, climate change context teaching, and digital learning with VR technology. Drawing from the findings of prior studies on these three components, this research develops a problem-based digital pedagogical model infrastructure integrated with VR technology to enhance students' critical thinking and climate change awareness. As far as the reviewed literature indicates, such a pedagogical model has not been developed before.

Exploring the sustainability of teaching climate change issues and advancing digital education innovations are essential references for further implementation of climate change mitigation efforts (Zhao et al., 2023). The proposed pedagogical infrastructure is designed as a digital system to support students' learning experiences in the specific context of climate change, integrated with VR technology. It follows five instructional phases: orientation to climate change issues/problems, organization of climate change knowledge structure, deep exploration of climate change problem-solving, presentation of climate change problem exploration results, and discussion and reflection on climate change issues. A detailed description of the learning activities in each phase of the problem-based digital pedagogical model integrated with VR technology is presented in Table 1.

Table 1. Digital pedagogical model based on climate change issues integrated with VR technology

Learning Phases	Learning Activities
1. Orientation toward climate change issues.	• Introducing students to issues and problems related to climate change.
2. Organization of the climate change knowledge structure.	• Facilitating students in organizing climate change information through intensive discussions to build knowledge about climate change.
3. Deep exploration of climate change problem-solving.	• Facilitating students to work in groups to conduct in-depth exploration of specific climate change issues using VR video technology.
4. Presentation of the results of climate change problem exploration.	• Asking students to present the results of their exploration on climate change problem-solving based on VR videos. The presentation should cover the causes, impacts, and proposed mitigation measures.
5. Discussion and reflection on climate change issues.	• Encouraging discussions among students about the results of their exploration and reflecting on what they have learned, the challenges they faced, and how this learning experience has influenced their understanding of climate change.

Pedagogical Model Testing

The digital pedagogical model based on climate change issues integrated with VR technology was tested for its validity, practicality, and effectiveness in enhancing students' critical thinking skills and awareness of climate change issues. The model's validity was evaluated through a validation process involving five expert validators. Meanwhile, the practicality and effectiveness of the model were tested by implementing it with students within an experimental framework. The results of the model's validity testing, focusing on content and construct validity, are presented in Table 2.

Table 2. Model validation data results

Validation aspects	Average validity score	Criteria
Content validity	4.10	Valid
Construct validity	4.20	Very valid
Average score	4.15	Valid

Based on the validity testing results of the digital pedagogical model based on climate change issues integrated with VR technology, an average validation score was obtained, indicating that the model is valid in terms of content and construct. The aspect of content validity achieved an average score of 4.10, classified as valid, showing that the content presented in this model aligns with the intended learning objectives. Meanwhile, the construct validity aspect received an average score of 4.20, categorized as very valid, indicating that the structure and design of the model align with relevant theories and principles of learning. Overall, the average validation score of 4.15 confirms that this pedagogical model can be effectively applied in the context of climate change education to enhance students' critical thinking and awareness.

Subsequently, the validated model was implemented with students to evaluate its practicality and effectiveness. The practicality of the model was assessed based on its implementation. The implementation data observed by two observers are presented in Table 3.

Table 3. Implementation data of the pedagogical model

Learning Phases	Average observation score	Criteria
1. Orientation toward climate change issues.	5.00	Very good
2. Organization of the climate change knowledge structure.	5.00	Very good
3. Deep exploration of climate change problem-solving.	4.50	Very good
4. Presentation of the results of climate change problem exploration.	5.00	Very good
5. Discussion and reflection on climate change issues.	4.50	Very good
Average score	4.80	Very good

The average score for the implementation of the learning process was 4.80, categorized as very good. This indicates that the pedagogical model is practical in its implementation phase. Furthermore, the effectiveness of the model was evaluated, particularly in enhancing students' critical thinking and awareness of climate change issues. The data on students' critical thinking skills are presented in Table 4, Table 5, and Figure 2.

Table 4. Data on students' critical thinking skills by indicator

Indicator	Group	N	Mean	SD	Criteria
1. Interpretation	Posttest	38	7.026	2.033	Critical
	Pretest	38	4.368	2.443	Moderately critical
2. Analysis	Posttest	38	6.026	2.455	Critical
	Pretest	38	1.842	1.534	Not critical
3. Evaluation	Posttest	38	5.711	2.335	Moderately critical
	Pretest	38	1.658	1.744	Not critical
4. Inference	Posttest	38	5.763	2.625	Moderately critical
	Pretest	38	1.605	1.480	Not critical
5. Explanation	Posttest	38	4.763	1.618	Moderately critical
	Pretest	38	1.289	1.271	Not critical
6. Self-Regulation	Posttest	38	6.026	2.112	Critical
	Pretest	38	1.816	2.154	Not critical

Based on Table 4, the study results indicate a significant improvement in students' critical thinking skills after the intervention of the problem-based pedagogical model integrated with virtual reality technology. For the interpretation indicator, the average post-test score reached 7.026, classified as critical, an increase from the pre-test score of 4.368, which was only moderately critical. The analysis indicator also showed a dramatic improvement from 1.842 (not critical) to 6.026 (critical). For the evaluation indicator, the average score increased from 1.658 (not critical) to 5.711 (moderately critical). Similarly, the inference and explanation indicators showed comparable improvements, with self-regulation reaching the critical category in the post-test with a score of 6.026, up from the pre-test score of only 1.816.

Table 5. Average score of students' critical thinking skills

Group	N	Mean	SD	Criteria
Pretest	38	2.097	1.158	Less critical
Posttest	38	5.886	1.650	Moderately critical

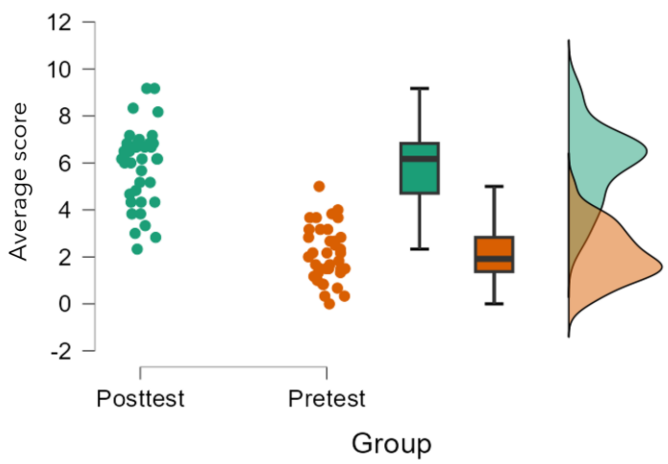

Figure 2. Descriptive plot of students' critical thinking skills

Table 5 presents the overall average of students' critical thinking skills. In the pre-test, the average score was in the less critical category with a score of 2.097. After the intervention, the average post-test score increased to 5.886, which falls into the moderately critical category, indicating that the implemented pedagogical model effectively improved students' critical thinking skills. Figure 2 reinforces the descriptive analysis results with visualizations in the form of boxplots and density plots, showing a significant increase in the post-test compared to the pre-test. The comparison of score distributions between the two groups reveals that students' post-test scores tend to be higher and more consistent, with smaller variations compared to the pre-test, demonstrating increased consistency and critical thinking skills after the intervention.

Furthermore, the data on students' awareness analysis results are presented in Table 6, Table 7, and Figure 3.

Table 6. Data on students' awareness by elements

Elements of awareness	Grup	N	Mean	SD	Criteria
1. Knowledge about Climate Change	Posttest	38	3.675	0.815	High
	Pretest	38	2.465	0.858	Low
2. Awareness of the Impacts of Climate Change	Posttest	38	3.754	0.855	High
	Pretest	38	2.991	0.976	Moderate
3. Attitudes toward Climate Change	Posttest	38	3.430	0.993	High
	Pretest	38	3.210	1.000	Moderate
4. Actions in Daily Life	Posttest	38	3.764	0.998	High
	Pretest	38	2.824	0.855	Moderate
5. Participation in Environmental Activities	Posttest	38	3.474	0.761	High
	Pretest	38	2.957	0.828	Moderate
6. Knowledge About Climate Change Mitigation	Posttest	38	3.650	0.853	High
	Pretest	38	2.325	0.818	Low
7. The Role of Education in Climate Change Issues	Posttest	38	3.465	0.898	High
	Pretest	38	3.053	1.190	Moderate

The result presented in Table 6, indicated that there is a significant increase in students' awareness regarding climate change issues after pedagogical model intervention. Table 6 shows improvements in all tested elements. In the element of knowledge about climate change, the average post-test score reached 3.675 (high category), an increase from 2.465 in the pre-test (low category). Awareness of the impacts of climate change also increased from 2.991 (moderate category) to 3.754 (high category). Students' attitudes toward climate change improved from 3.210 (moderate category) to 3.430 (high category). The element of daily life actions related to climate change showed an increase from 2.824 (moderate category) to 3.764 (high category). Participation in environmental activities also rose from 2.957 to 3.474 (high category). Knowledge about climate change mitigation significantly improved from 2.325 (low category) to 3.650 (high category), and the role of education in climate change issues increased from 3.053 (moderate category) to 3.465 (high category).

Table 7. Average score of students' awareness

Group	N	Mean	SD	Criteria
Pretest	38	2.831	0.673	Moderate
Posttest	38	3.602	0.730	High

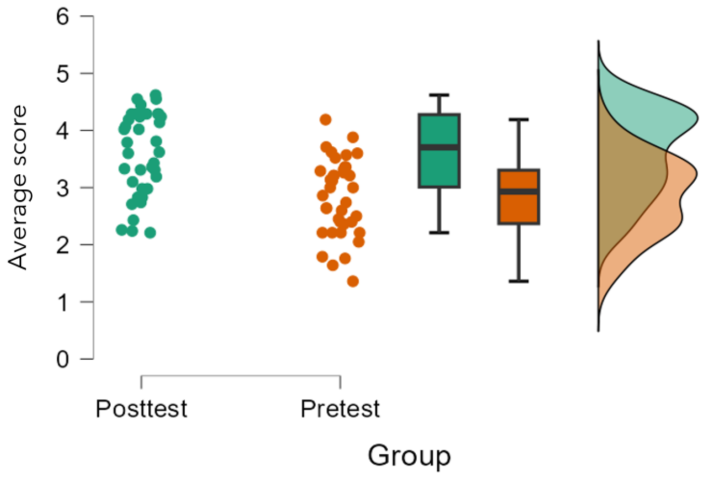

Figure 3. Descriptive plot of students' awareness

Table 7 presents the overall average of students' awareness, where the pre-test average score was in the moderate category at 2.831. After the intervention, the post-test average score increased to 3.602, which falls into the high category, indicating that the problem-based pedagogy with virtual reality integration effectively improved students' awareness of climate change issues. Figure 3 reinforces these results with visualizations in the form of boxplots and density plots showing that the distribution of students' post-test scores was higher and more consistent compared to the pre-test, highlighting the improvement in students' awareness after the learning intervention.

Regarding effectiveness, the study results show that after the intervention of the digital problem-based pedagogical model integrated with virtual reality technology, there was a significant increase in students' critical thinking skills and awareness. The average score of students' critical thinking skills increased from the "less critical" category in the pre-test to "moderately critical" in the post-test, and students' awareness of climate change issues also rose from the "moderate" category to the "high" category after the intervention. This improvement indicates that the developed pedagogical model is effective in enhancing students' critical thinking skills and awareness of climate change issues.

Overall, the study results demonstrate that the digital problem-based pedagogical model integrated with virtual reality technology is valid, practical, and effective in improving students' critical thinking skills and awareness of climate change issues. In terms of validity, the validation results show an average score of 4.15, which falls into the "valid" category. This reflects that the model has met the appropriate content and pedagogical structure standards aligned with learning objectives, particularly in improving critical thinking skills and awareness of climate change issues. This validation aligns with previous research emphasizing the importance of problem-based learning models in supporting the development of students' critical thinking and problem-solving skills (Akınoğlu & Tandoğan, 2007; Barak, 2020). Thus, the validity obtained in this study indicates that the proposed model has a strong theoretical foundation for application in the environmental education context.

The practicality of the model is also a key finding of this study. With an average score of 4.80 in the "very good" category, the model has proven to be practical and easy to implement in the field. This practicality indicates that teachers and students can implement the model without significant obstacles during the learning process. In the context of climate change education, the use of virtual reality technology and problem-based methods has been shown to facilitate deeper student engagement, allowing them to understand the impacts of climate change more interactively and vividly (Meijers et al., 2023; Zhang & A. Bowman, 2022). This practicality also aligns with the growing trend of digital learning, where technology-based learning not only enhances accessibility but also provides more meaningful learning experiences for students (Herodotou et al., 2020; Palvia et al., 2018).

In terms of effectiveness, the model successfully enhanced students' critical thinking skills significantly. The pre-test and post-test results showed an average improvement in critical thinking skills from the "less critical" to the "moderately critical" category. This improvement aligns with findings that Problem-Based Learning (PBL) is an effective approach in fostering the development of students' critical thinking skills (Han, 2017; Setyono et al., 2018). The use of virtual reality in this model also had a positive impact, as the technology enabled students to engage more deeply with complex environmental issues such as climate change (Zhang & A. Bowman, 2022). Additionally, students were encouraged to collaborate, analyze problems, and seek evidence-based solutions, which are crucial elements in the development of critical thinking skills (Calkins et al., 2020).

In addition to critical thinking skills, the model also effectively increased students' awareness of climate change issues. From the pre-test to the post-test, the average awareness score of students increased from the "moderate" category to the "high" category. This indicates that integrating virtual reality technology with problem-based learning not only impacts cognitive skills but also affects affective aspects such as awareness and attitudes toward environmental issues (Álvarez-Nieto et al., 2022; Asante et al., 2024). Students' awareness of climate change is crucial, given that it is one of the most pressing global challenges. By increasing students' knowledge and awareness of the impacts and solutions to climate change, the model successfully encouraged students to be more responsible and proactive in mitigation efforts (Kousar et al., 2022).

CONCLUSION

A digital pedagogical model based on climate change issues integrated with VR technology has been developed to enhance students' critical thinking and awareness regarding climate change. This prototype leverages the power of VR technology to create immersive and interactive learning experiences, enabling students to actively engage in the learning process. VR technology allows students to enter virtual environments simulating various climate change scenarios, so they not only learn the theory but also experience the tangible impacts of these issues. This contributes significantly to improving students' understanding and awareness of climate change.

The PBL model employed in this prototype emphasizes exploration and solving real-world problems currently faced by the world. The combination of PBL and VR encourages students to identify problems, analyze their causes, and propose innovative solutions to the challenges posed by climate change. This method has been proven to significantly enhance students' critical thinking skills, as evidenced by research findings showing a substantial improvement in average critical thinking skills from pretest to posttest. Moreover, students became more engaged in teamwork and effective communication, which are essential elements of collaborative learning.

The findings of this study demonstrate that the digital pedagogical model based on climate change issues integrated with VR technology is valid, practical, and effective. The model's validity is reflected in the validation results, which yielded an average score of 4.15, categorized as valid. The practicality of the model is evidenced by its implementation in learning, which received a score of 4.80, categorized as "very good." The model's effectiveness is also proven through significant improvements in students' critical thinking skills and awareness of climate change issues. Therefore, this pedagogical model can play a crucial role in cultivating a generation of students who are more environmentally conscious and better prepared to tackle global challenges related to climate change in the future.

Overall, this model makes a significant contribution to interactive and technology-based learning, focusing not only on general knowledge acquisition but also on the development of critical thinking skills and environmental awareness needed to address real-world climate change problems.

LIMITATIONS

This study has several limitations that should be considered. First, the scope of implementation was limited to a single high school in eastern Indonesia, which may restrict the generalizability of the findings to other educational contexts. Second, the use of VR technology required specific infrastructure and equipment, which may not be readily available in all schools, particularly in rural or under-resourced areas. Third, the study focused primarily on measuring critical thinking skills and climate change awareness, potentially overlooking other cognitive or affective domains that could also be impacted by the pedagogical model. Lastly, the research timeline was relatively short, making it difficult to assess the long-term retention of critical thinking skills and awareness improvements among students.

RECOMMENDATIONS

Future studies should expand the implementation of this pedagogical model to a broader range of schools across different regions and socioeconomic contexts to enhance its generalizability. Additionally, efforts should be made to develop more cost-effective and accessible VR tools to ensure broader adoption, especially in underprivileged schools. Researchers are encouraged to explore the impact of this model on other educational outcomes, such as students' collaborative skills, creativity, and ethical reasoning. Finally, longitudinal studies are recommended to evaluate the long-term effects of the pedagogical model on students' critical thinking skills, climate change awareness, and their subsequent actions in addressing environmental challenges.

Author Contributions

The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Conflict of Interests

The authors declare no conflict of interest.

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