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Implementing XR-Based Virtual Science Lab for Inquiry-Based Learning

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Abstract. Extended Reality (XR) combines virtual and real elements, offering learners realistic and immersive environments to explore complex concepts and ideas. As XR technology evolves, its applications in education continue to expand, particularly in delivering innovative learning experiences. Notably, STEM fields are increasingly adopting XR-based educational methods to make science learning more engaging and effective. This study aims to develop an XR-based virtual science laboratory that integrates an inquiry-based learning model to enhance science education. The XR science lab enables learners to conduct experiments that are difficult or impossible to perform in traditional classroom or real-world settings, such as simulating hazardous conditions or exploring microscopic processes. Furthermore, the lab includes an integrated science notebook, allowing learners to hypothesize, document experimental procedures, analyze data, and validate findings. This approach helps learners deepen their understanding of scientific principles while applying inquiry and problem-solving methods. By merging XR technology with the inquiry-based learning model, this study provides a framework for promoting active, experiential learning in STEM education, suggesting a future direction for STEM pedagogy and expanding the potential applications of XR technology in educational contexts.

Keywords: Extended Reality, STEM Education, Virtual Science Lab.

1 Introduction

As society transitions into the information age, STEM education has gained global attention. However, traditional STEM education methods face challenges such as limited access to experimental equipment, safety concerns, and time constraints [1]. Extended Reality (XR) technology, which integrates virtual and real elements to create immersive learning environments, has emerged as a pivotal tool for supporting STEM education [2-4]. Notably, XR enables the safe simulation of scenarios that are challenging to experience in the real world, encouraging active learner engagement [5]. By facilitating immersive and interactive learning experiences, XR technology demonstrates significant potential for enhancing science education.

Inquiry-Based Learning (IBL) is a science education model that emphasizes active learner participation, and the 5E model provides a structured framework for its effective implementation [6-7]. This study aims to develop an educational model integrating XR technology and IBL, designing an XR-based virtual science laboratory where learners can safely and immersively conduct experiments that would otherwise be difficult in real-world settings. Through this approach, the study seeks to enhance learning outcomes and promote educational equity.

2 Literature Review

2.1 XR Technology and STEM Education

XR is an innovative educational tool that enhances immersion and interactivity, encompassing the characteristics of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in a broad and integrative concept [4]. VR provides a three-dimensional virtual space [8], AR overlays virtual objects onto real-world scenes to enhance interaction [9], and MR combines both technologies to emphasize integrated applications [10]. These technologies share key attributes—immersion, realism, and interactivity—allowing XR to seamlessly connect virtual and real environments, enabling learners to intuitively explore concepts [11]. By integrating immersive and interactive technologies, XR has the potential to enhance or transform real-world experiences, offering learners opportunities to intuitively explore complex concepts and ideas.

In STEM education, XR enhances student motivation, engagement, and comprehension, particularly in learning abstract concepts [12]. STEM education integrates science, technology, engineering, and mathematics to help students apply concepts from the curriculum [13]. Benyeogor et al. (2021) [14] emphasized that STEM education should integrate academic theories and practices into a model that enables students to understand and solve problems. Through hands-on practice, students deepen their understanding of learned concepts, acquiring and applying skills rather than merely memorizing textbook content. XR creates practical learning environments using avatars and holograms, facilitating the visualization of complex concepts and encouraging active learner participation [2]. This demonstrates the potential for more effective STEM education through XR.

2.2 Extended Reality (XR) Based Science Education and Inquiry Learning (5E Model)

In the context of science education employing XR technologies, the IBL model emerges as a viable instructional approach. Unlike traditional teacher-centered methods, the IBL model is an active learning framework [15]. In inquiry-based science instruction, students engage in activities and thought processes similar to those scientists use to generate new knowledge. Traditional teaching methods often rely on unidirectional, didactic instruction, where students passively absorb information without questioning the instructor [16]. This approach tends to overlook critical thinking and integrative concepts essential for scientific literacy [17]. Science educators emphasize the importance of inquiry-based approaches that stimulate students' interest in science, allow them to gather evidence through experimentation, and enable logical problem-solving [18]. Learning cycles vary from 4E to 5E, and even to 7E stages. This study employs the 5E instructional model by Bybee et al. (2006) [19], comprising the following:

(1) Engage: The teacher identifies students' prior knowledge and misconceptions
(2) Explore: Students conduct experiments and explore new concepts
(3) Explain: Students articulate their experiences and teachers provide additional explanations
(4) Elaborate: Students apply the acquired knowledge and skills to new situations
(5) Evaluate: Teachers assess students' understanding and progress

During the exploration phase, technology can assist in designing experiments, gathering data, and analyzing the collected information. The use of digital technology in the learning process can facilitate lesson visualization, ease teachers' tasks, and broaden students' perspectives [20]. Additionally, digital technology effectively supports learners in forming hypotheses and conducting inquiries [21]. XR technology can further support IBL by visualizing complex scientific concepts or virtually recreating realistic experimental environments. Therefore, XR technology can be used to implement a virtual laboratory that enhances the exploration phase of the 5E model. By utilizing XR technology, a 3D virtual simulation resembling an actual laboratory can be created, allowing students to conduct experiments virtually and obtain immediate results.

3 Design and Development

3.1 Design

To design an XR-based virtual science laboratory, an analysis of learners and instructional content was conducted. The instructional materials employed for the XR-based virtual science laboratory design were drawn from the South Korean middle school Science II textbook, with a focus on "environmental factors affecting photosynthesis." The target learners were second-year middle school students. According to the 2023 Trends in International Mathematics and Science Study (TIMSS) conducted by the International Association for the Evaluation of Educational Achievement (IEA), South Korean students demonstrated lower levels of attitude towards science compared to their international peers [22]. An analysis of existing learning environments and activities revealed limitations in effectively achieving learning objectives and meeting achievement standards. For example, the three environmental factors influencing photosynthesis—light intensity, carbon dioxide concentration, and temperature—are difficult to manipulate in physical experimental settings. This difficulty in controlling variables often prevents students from obtaining experimental results that align with textbook content. Additionally, time constraints during lessons, combined with learners' limited observation and measurement skills, hinder the derivation of accurate experimental results [23]. These challenges undermine the efficiency of IBL and hinder academic achievement. Therefore, there is a need to establish an XR environment that allows for the easy manipulation of various environmental factors and enables precise and rapid visualization of changes in photosynthesis rates in response to these factors.

To facilitate effective science learning, the instructional process utilizing the XR-based virtual science laboratory was designed based on the 5E IBL model. In the Engage phase, questions based on learners' actual experiences are used to stimulate motivation, which helps enhance the quality of hypothesis formulation. During the Explore phase, learners formulate hypotheses on a worksheet and conduct experiments in the XR environment to test them. The virtual laboratory clearly presents the changes that occur as learners manipulate variables, helping them validate their hypotheses. In the Explain phase, learners analyze the results of their inquiry activities and create graphs on their learning sheets to examine the relationship between environmental factors and the rate of photosynthesis. By constructing these graphs, learners explain the results and validate their hypotheses, while the instructor provides feedback. In the Elaborate phase, learners apply the content they learned through the virtual laboratory to new contexts using the learning sheets. Additional experiments can then be conducted within the XR-based virtual science laboratory. Finally, in the Evaluate phase, a concluding quiz is administered to assess the content learned, further reinforcing a deeper understanding of scientific concepts. This instructional process is visually represented in a flowchart (see in Fig. 1).

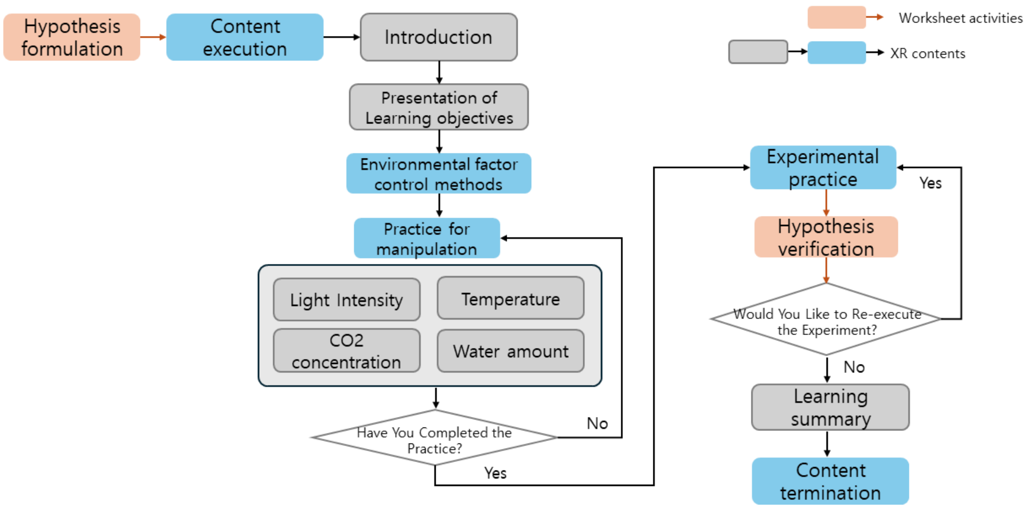

Fig. 1. Flowchart.

In the XR-based virtual science laboratory, manipulable variables were designed to take advantage of easily adjustable factors that are difficult to manipulate in real-world experimental settings. The temperature variable, while a significant factor affecting photosynthesis, is rarely utilized in physical experiments, making it inaccessible for learners in real-world environments. Similarly, light intensity and carbon dioxide concentration, though commonly manipulated in actual experiments, present challenges in terms of observation and are often measured indirectly. The water quantity variable was included to help learners overcome the misconception that it directly impacts the rate of photosynthesis, thereby facilitating conceptual clarity through experimentation. To ensure precise identification of the factors affecting photosynthesis, the system was designed so that the manipulation of one variable automatically restricts the control of others. This approach allows learners to observe environmental changes in real time as each variable is adjusted, enabling straightforward hypothesis testing and promoting a deeper understanding of scientific concepts.

3.2 Development

To implement the XR-based virtual science laboratory, a storyboard was first developed. This storyboard was designed based on a flowchart, visually representing the scenes for each stage of the learning process. It included both textual information and components for each stage, such as audio and XR interactive elements. The developed storyboard was reviewed by two in-service teachers and two experts with doctoral degrees in educational technology. Feedback was provided on various aspects, including the use of precise academic terminology, modifications to the graph depicting the stages of photosynthesis, the addition of experimental steps for hypothesis testing, and the provision of text-based feedback for quiz responses. Based on this expert feedback, the storyboard was revised and used to develop the XR-based virtual science laboratory. The completed storyboard is illustrated in Figure 2.

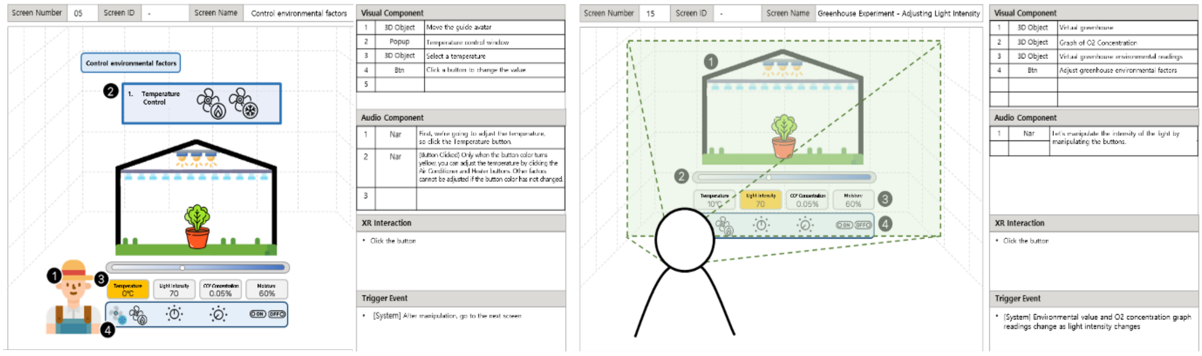

Fig. 2. Part of storyboard for XR-based virtual science lab.

The virtual laboratory, leveraging XR technology, was developed using Unity and designed for Microsoft's HoloLens 2. This head-mounted display (HMD) overlays digital 3D holograms onto the real world, minimizing issues such as cyber-sickness and enhancing the user experience. Additionally, HoloLens 2 provides a customized interface by recognizing users' gaze and hand movements, allowing learners to interact with virtual objects in real-time through physical gestures and fostering an immersive learning experience. Learners interact with virtual objects and click virtual buttons while wearing the device. To support the development of mixed reality within Unity, the Mixed Reality Toolkit (MRTK) was used. An avatar was created using Ready Player Me to enhance learner engagement and immersion. The avatar's voice was synthesized using Clova Dubbing, and its animations were generated with Mixamo. This avatar aids learning by providing appropriate gestures and verbal feedback during the inquiry process. Additionally, the virtual laboratory environment was designed to enable interaction through the learners' physical movements, offering both visual and auditory cues to support the intuitive acquisition of scientific concepts. An example of the developed XR virtual science laboratory environment is presented in Figure 3.

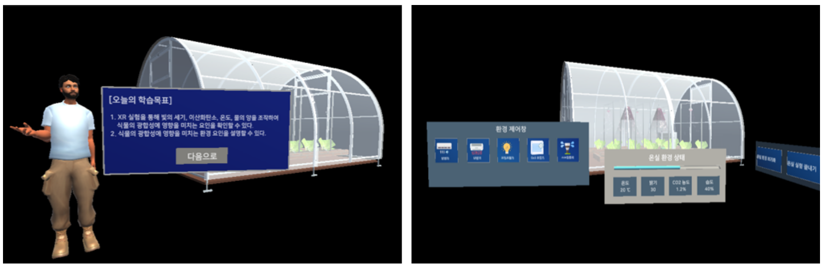

Fig. 3. Example of XR-based virtual lab.

4 Conclusion

This study aimed to design and develop a virtual science laboratory that effectively integrates XR technology with the 5E IBL model for STEM education. The developed XR-based virtual science laboratory enables learners to investigate factors affecting photosynthesis. By engaging with the virtual laboratory and accompanying learning materials, learners formulate hypotheses, analyze experimental results to understand scientific principles, apply their understanding to different contexts, and evaluate their learning processes. This sequential process deepened learners' scientific inquiry skills. The virtual science laboratory serves as an educational tool that overcomes several limitations of traditional science education. It addresses the physical constraints of laboratory equipment, provides opportunities to safely conduct hazardous experiments, and fosters scientific reasoning and problem-solving skills by enhancing learner immersion and active engagement.

However, the study has several limitations. First, a usability evaluation to clearly demonstrate the effectiveness of the XR-based learning environment was not conducted. Second, the developed content focuses on a specific topic, and its potential for expansion to other scientific concepts remains unverified. Third, the accessibility of hardware and software required for XR technology may be limited in certain educational settings. Future research should conduct usability evaluations across diverse learner populations and expand the scope of the virtual science laboratory by developing content for additional topics. Long-term analyses of learning outcomes are also needed, along with the exploration of innovative interface designs and interaction methods to further enhance learner engagement and immersion. Through these additional studies, the educational application of XR technology can be further advanced, contributing to the transformative development of STEM education.

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References

1. Putri, L. A., Permanasari, A., Winarno, N., & Ahmad, N. J.: Enhancing students' scientific literacy using virtual lab activity with inquiry-based learning. Journal of Science Learning, 4(2), 173–184 (2021).
2. Chiang, Y. C., & Liu, S. C.: The effects of extended reality technologies in STEM education on students' learning response and performance. Journal of Baltic Science Education, 22(4), 568–578 (2023).
3. Aguayo, C., & Eames, C.: Using mixed reality (XR) immersive learning to enhance environmental education. The Journal of Environmental Education, 54(1), 58–71 (2023).
4. Kosko, K. W., Ferdig, R. E., & Roche, L.: Conceptualizing a shared definition & future directions for extended reality (XR) in teacher education. Journal of Technology & Teacher Education, 29(3), 257–277 (2021).
5. Hmoud, M., Swaity, H., Karram, O., Shibli, H., Swaity, S., & Daher, W.: High school students' engagement in biology in the context of XR technology. IEEE Access, 11, 137053–137066 (2023).
6. Safkolam, R., Madahae, S., & Saleah, P.: The effects of inquiry-based learning activities to understand the nature of science of science student teachers. International Journal of Instruction, 17(1), 479–496 (2024).
7. Koyunlu Unlu, Z. & Dokme, I.: The effect of technology-supported inquiry-based learning in science education: Action research. Journal of Education in Science, Environment and Health (JESEH), 6(2), 120–133 (2020).
8. Karampelas, A.: Artificial Intelligence and Machine Learning in the STEAM classroom: Analysis of performance data and reflections of international high school students. Hellenic Journal of STEM Education, 1(2), 59–66 (2020).
9. Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R.: The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses—Theoretical background and empirical results. British Journal of Educational Technology, 51(3), 611–628 (2020).
10. Lee, Y.: Development and effectiveness analysis of artificial intelligence STEAM education program. Journal of the Korean Association of information Education, 25(1), 71–79 (2021).
11. Huang, P. S., Chiu, P. S., Huang, Y. M., Zhong, H. X., & Lai, C. F.: Cooperative mobile learning for the investigation of natural science courses in elementary schools. Sustainability, 12(16), 6606 (2020).
12. Chng, E., Tan, A. L., & Tan, S. C.: Examining the use of emerging technologies in schools: A review of artificial intelligence and immersive technologies in STEM education. Journal for STEM Education Research, 6(3), 385–407 (2023).
13. Lee, Y., & Kim, E.: An analysis of learning outcomes and learning satisfaction of project-based learning in non-face-to-face learning environment. The Journal of the Korea Contents Association, 21(6), 814–825 (2021).
14. Benyeogor, M., Olakanmi, O., Nnoli, K., & Gwani, M.: Edu-Rover: Application of unmanned vehicle systems for robotics and STEM education in Nigeria. EAI Endorsed Transactions on Creative Technologies, 8(26) (2021).
15. Ünlü, Z. K., & Dökme, I.: The effect of technology-supported inquiry-based learning in science education: Action research. Journal of Education in Science Environment and Health, 6(2), 120–133 (2020).
16. Stofflet, R. T.: Putting constructivist teaching into practice in undergraduate introductory science. The Electronic Journal for Research in Science & Mathematics Education (1999).
17. Yore, L. D.: What is meant by constructivist science teaching and will the science education community stay the course for meaningful reform?[Electronic Version]. Journal of Science Education, 5(4) (2001).
18. Secker, C. V.: Effects of inquiry-based teacher practices on science excellence and equity. The Journal of Educational Research, 95(3), 151–160 (2002).
19. Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. The BSCS 5E instructional model: Origins and effectiveness. Colorado Springs, Co: BSCS, 5(88–98) (2006).
20. Bozdogan, A. E.: The effects of instruction with visual materials on the development of preservice elementary teachers' knowledge and attitude towards global warming. Turkish Online Journal of Educational Technology-TOJET, 10(2), 218–233 (2011).
21. Beishuizen, J., Wilhelm, P., & Schimmel, M.: Computer-supported inquiry learning: Effects of training and practice. Computers & Education, 42(4), 389–402 (2004).
22. TIMSS 2023 Homepage, https://timss2023.org/results/students-like-science/, last accessed 2025/01/14.
23. Moon, K., & Kim, Y.: Secondary school students` understanding and performance of experiments on photosynthesis and respiration. Biology Education, 36(4), 537–554 (2008).