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Earth Science Simulations with Generative Artificial Intelligence (GenAI)

Dr Yoon-Sung Choi
Pusan National University, Republic of Korea

Abstract

This study investigates the practical characteristics of Earth science mock lessons utilising generative artificial intelligence (GenAI). To accomplish this, the researcher developed a one-session Earth science mock lesson employing GenAI, following a five-week preparation phase. Three pre-service teachers from the Earth Science Education Department at University A's College of Education participated in the study. Data collection included all written materials related to the GenAI-integrated instructional plan (lesson plans, instructional resources, activity sheets, all texts used in interactions with the GenAI, and pre-service teachers' self-assessments following the mock lesson), as well as video footage and audio recordings of the mock lesson, and semi-structured interviews conducted post-lesson. The GenAI-enhanced Earth science lesson plans were analysed using the TIAR evaluation rubric to explore the strengths, considerations, and potential of GenAI-integrated instruction. Furthermore, anticipated learning outcomes were examined using an AI literacy framework. Findings indicate that the Earth science mock lessons demonstrated intentional GenAI utilization regarding learning objectives, instructional models and strategies, and assessment. While the lessons revealed instrumental advantages of GenAI in an instructional context, the need for a critical approach to avoid over-reliance on the technology was emphasized. Anticipated learning outcomes from the mock lessons were found to encompass the affective, behavioural, cognitive, and ethical domains of AI literacy. This study empirically applies GenAI in Earth science education, examining GenAI-related learning outcomes and is anticipated to positively impact pre-service teachers' pedagogical competencies through technology-enhanced instruction.

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Introduction

The emergence of Generative Artificial Intelligence (GenAI) initially created a significant impact across various sectors of society. However, interactions with GenAI can occasionally lead to skepticism due to its occasional lack of objectivity concerning scientific knowledge and facts (Elmas et al., 2024). Over time, with advancements in models such as ChatGPT-4 and other technological improvements, society has moved beyond concerns about knowledge accuracy and errors, and now considers how GenAI can be utilized for educational purposes (Roll & Wylie, 2016). Given the rapid advancement of GenAI technology, its role in education is increasingly seen as an inevitable transformation within school settings.

GenAI's potential represents a groundbreaking leap forward in educational technology, enabling the creation of enriched learning experiences and supporting personalized learning and skill development in unprecedented ways (Holmes et al., 2019). Its significance lies in the ability to generate content, simulate complex scenarios, and provide immediate, adaptive feedback tailored to individual learner needs (Chen et al., 2020). This transformative capability positions GenAI as an invaluable tool for educators, enabling the design of interactive learning environments that promote deeper and more meaningful engagement from students. The scope of GenAI application spans from automating administrative tasks and creating personalized lesson plans to developing immersive virtual learning environments and supporting real-time language translation (Bakdash et al., 2024; Chiu et al., 2023a; Chiu, 2024; Liao et al., 2024).

As GenAI continuous to evolve, integrating it into educational context not only promised to enhance the efficiency of teaching and learning but also foster an inclusive, student-based learning paradigm capable of adapting to diverse learning styles and needs. This highlights the importance of ongoing research and development to maximize GenAI's potential while ensuring its effective and ethical deployment in educational settings (Holmes et al., 2022).

Prior research on the educational application of GenAI has primarily focused on language-based learning and the development of tools and systems, with particular attention given to the significance of learning algorithms and ethical considerations surrounding the rights associated with GenAI use (Berendt et al., 2020; McStay, 2020; Verma et al., 2023). GenAI has shown potential to enhance learners' affective domain such as engagement, attitudes, motivation (Chiu et al., 2023b; Dettewiler et al., 2017; Hagger & Hamilton, 2018) and achievement through innovative features, such as delivering personalized learning experiences, providing feedback, simulating complex problem-solving scenarios or other ways. (Noh & Lee 2020; Sisman et al., 2024; Wang et al., 2024; Zhai et al., 2024). Chiu (2023b) demonstrated that AI-based learning tools could be integrally utilized across four primary educational domains; instruction, learning assessment, and administration.

Despite this potential, there remain several limitations to GenAI's curricular applications. Berendt et al., (2020) suggested a need for empirical research on interpreting GenAI from an educational perspective and applying it to pedagogical methods. They noted that current GenAI research often overlooks the multifaceted challenges and potential risks associated with GenAI implementations. Similarly, Williamson and Eynon (2020) observed that the scientific impact of GenAI on practical learning, particularly within K-12 education, has not yet been conclusively established. This raises caution against a blind or uninformed adoption of GenAI technology.

In the context of science education, it has explored the types of inquiries that ChatGPT can facilitate, as well as its potential as a teaching and research tool (Cooper, 2023). Some studies discuss the utility of ChatGPT in learning by categorizing it into area such as critical reasoning, digital literacy, and the development of foundational skills (Chiu, 2023; Cooper, 2023). The educational use of ChatGPT has also yielded positive outcomes in terms of students' academic performance, subject-specific competencies, digital literacy, and psychological factors like motivation and a sense of security in technology-enhanced learning environments (Almasri, 2024). Aligned with these findings, numerous case studies on the application of GenAI in science education are emerging. These studies include practical examples of using chatbots and examining question types facilitated by ChatGPT, particularly targeting elementary school students (Byeon & Kwon, 2023; Chang et al., 2023; Lee et al., 2023; Shin & Baek, 2024; Topal et al., 2021).

Despite prior research, significant gaps remain in the educational application of generative AI (GenAI) for science instruction, particularly regarding the lack of guidelines and resources to support teachers and pre-service teachers in effectively utilizing GenAI (Choi & Chung, 2024). Specifically, there is limited guidance on how to teach with GenAI, what materials to use, and how to create engaging and effective instructional experiences (Choi, 2024; Yau et al., 2023). To address these limitations, this study aims to analyse the planning and practical characteristics of Earth Science simulation lessons utilizing GenAI, with the objective of identifying effective and educationally sound application strategies for GenAI. Through this approach, the study seeks to provide empirical examples of how GenAI can be implemented in actual educational settings. The purpose of this study is to analyse the practical characteristics of Earth Science simulation lessons employing GenAI. To achieve this, three research questions have been formulated.

1. What is the scope of ChatGPT's application that pre-service Earth Science teachers can utilise in science instruction?
2. What are the advantages and considerations for pre-service Earth Science teachers in using ChatGPT within science lessons?
3. How might the use of ChatGPT in science instruction influence students' AI literacy?

Literature

Generative artificial intelligence (GenAI) in higher education

Language education, particularly within the context of higher education, is deeply influenced by social factors such as gender, race, and cultural backgrounds (Kubota & Mota, 2024). These factors play a significant role in shaping learners' experiences and outcomes. In this setting, GenAI has emerged as an innovative tool that can address these complexities and foster inclusive learning environments (Moore, 2024).

GenAI has shown significant potential in supporting marginalized identities in education. For instance, previous research illustrates how learners manage their identities in classroom settings and how GenAI can reflect and amplify these experiences (Moore, 2024). Also, it analyses the impact of accent bias on social judgments and propose GenAI as a tool to mitigate such prejudices (Kang & Yaw, 2024). Research on learners with disabilities further highlights how GenAI can

address the unique linguistic and cultural challenges faced by these individuals (Bhattacharya, 2024).

The applications of GenAI extend beyond language education to other subject areas such as science enabling tailored learning experiences to meet individual needs (Cooper, 2023). By incorporating cultural and linguistic diversity, GenAI can enhance inclusivity and engagement for a wider range of learners. However, its use also raises ethical concerns. It addresses systemic anti-Black sentiments in educational materials, advocating for GenAI's role in rectifying such biases (Anya, 2024). Likewise, it emphasizes the need for a decolonial approach in integrating GenAI into education, underscoring the importance of ethical data practices and responsible design (Kubota & Motha, 2024).

Recently, GenAI's use has expanded from language education to specific academic disciplines, including science, social studies and STEM, where it can provide personalized learning experiences (Cooper, 2023; Cheng et al., 2024; Li et al., 2025). By reflecting cultural and linguistic diversity, GenAI has the potential to increase accessibility and engagement among a broader range of students. GenAI offers great promise in addressing social inequalities and improving learning efficiency in higher education. Future research should prioritize validating its effectiveness and ensuring ethical practices. By doing so, GenAI can lead the way to more inclusive and equitable educational practices across diverse contexts.

Science teaching and learning with GenAI

GenAI in science education is transforming learning and teaching practices by personalizing instruction and fostering task engagement (Saúde et al., 2024). Instructors are leveraging AI-powered tools like intelligent tutoring systems to provide tailored feedback, adapting to individual students' learning paces and styles. These systems enhance inquiry-based learning approaches, allowing students to explore scientific concepts interactively (Wahyono et al., 2019; Kotis, 2024a). For example, ChatGPT has been used to create dynamic teaching materials, such as interactive quizzes and lesson plans, that align with inquiry-based and experiential learning models (Goodman et al., 2024; Powell & Courchesne, 2024). These practices are grounded in constructivist learning theories that emphasize critical thinking and collaboration, ensuring that students actively engage with content through problem-solving tasks (Daher et al., 2023; Taani & Alabidi, 2024).

Educators are also exploring the role of GenAI in building students' competencies beyond traditional learning(Al Darayseh, 2024). By simulating real-world scientific problems, GenAI encourages learners to apply theoretical knowledge practically. This approach helps bridge the gap between abstract concepts and their applications, particularly in STEM fields (Cheng et al., 2024). Moreover, the integration of GenAI is fostering a culture of curiosity and exploration among students, supporting their development as future scientists and engineers (Almasri, 2024). However, these advancements come with challenges. Teachers must understand the pedagogical implications of these technologies to effectively incorporate them into their lessons. Training programs that equip educators with the necessary skills to deploy GenAI tools responsibly are essential to maximizing their potential while minimizing misuse (Jalon et al., 2024; Kotis, 2024b; Zhai, 2024).

Ethical issues with GenAI in science education

The integration of GenAI in science education raises several ethical concerns, primarily regarding data privacy, bias, and equitable access. GenAI algorithms are trained on extensive datasets, which may contain biases that can disadvantage underrepresented groups. This could exacerbate educational inequities if not addressed proactively (Adams et al., 2022; Airaj 2024; Tang et al., 2024). For instance, biased AI responses could misrepresent scientific facts or favour certain demographics, impacting the inclusivity of education. Privacy concerns also emerge with the use of GenAI in classrooms. Personalized learning systems often require the collection of sensitive student data to tailor educational experiences, which raises questions about data security and ownership (Airaj, 2024; Tang et al., 2024). These risks necessitate robust data governance frameworks to ensure that students' information is protected while enabling meaningful educational innovation. Another critical ethical issue is the potential devaluation of human agency in learning. Relying excessively on AI-generated content risks turning students into passive recipients of information, undermining their ability to critically assess knowledge. Educators must therefore focus on fostering AI literacy, equipping students with the skills to evaluate AI outputs critically and integrate them thoughtfully into their learning processes (Folmeg et al., 2024; Zhai, 2022). Ethical guidelines and teacher training are vital to promoting responsible GenAI use while safeguarding educational integrity and student welfare (Adel et al., 2024; Bourton et al., 2017).

Four dimensions of AI literacy

AI literacy has become an essential part of higher education, combining the knowledge, skills, and attitudes needed to effectively engage with AI technologies (Chiu, 2024). The ABCE framework by Ng et al. (2024a) highlights four key dimensions of AI literacy: affective, behavioural, cognitive, and ethical, offering a holistic way to evaluate and enhance students' AI proficiency. The affective dimension focuses on learners' emotional responses to AI education, including intrinsic motivation, self-efficacy, and career interest (Ng & Chu 2021). Developing confidence and enthusiasm in AI concepts promotes deeper engagement and long-term interest (Ng et al., 2024). Positive emotional connections to AI learning can enhance students' interactions with these technologies in academic and professional contexts (Ng et al., 2024a). The behavioural dimension emphasizes actions and collaboration within AI learning environments (Ng et al., 2021). Research shows that collaborative projects, such as AI-driven simulations and group challenges, significantly improve practical understanding and engagement with AI technologies (Ng et al., 2024a). The cognitive dimension involves acquiring knowledge and critical thinking skills (Ng et al., 2021). This includes understanding AI principles, applying tools in real-world contexts, and critically evaluating AI systems. Activities like coding workshops and problem-solving exercises help students connect theoretical knowledge with practical applications, fostering skills for creating and analyzing AI-driven solutions (Ng et al., 2023; Ng et al., 2024b).

The ethical dimension focuses on responsible AI use and societal impacts (Ng et al., 2021; Gouseti et al., 2024). Key aspects include understanding biases, protecting data privacy, and promoting accountability and transparency in AI systems. Educators should integrate discussions about AI's ethical implications into the curriculum to help students critically assess its social and moral consequences (Gouseti et al., 2024). This equips learners to make informed decisions about deploying AI technologies responsibly (Ng et al., 2023). Incorporating these dimensions

into education provides a comprehensive way to build AI literacy (Ng et al., 2024b). By addressing emotional engagement, collaboration, critical thinking, and ethics, educators can prepare students to excel in AI-driven environments. Further research is necessary to validate these frameworks and explore their broader applications (Ng et al., 2023; Ng et al., 2024b;).

Method

Procedure

This study was conducted in five stages. First, a literature review was conducted to analyse previous research on the educational applications of GenAI, specifically examining content necessary for pre-service teacher training aimed at applying GenAI in K-12 education. Second, participants were recruited for the study. Students enrolled in the Department of Earth Science Education at the College of Education at University A, located outside the metropolitan area, were invited to participate. Participation was voluntary, and students who registered for a course on Educational Application of GenAI were included. Third, data collection was carried out. The researcher provided foundational training and guidance to pre-service teachers on GenAI usage, after which the participants designed a one-session Earth Science simulation lesson utilizing ChatGPT. During the lesson design phase, al written materials including lesson plans, instructional resources, activity sheets, and records of interactions with ChatGPT were collected. During the lesson implementation phase, the pre-service teachers' simulation lessons were video recorded, and audio recordings, along with text-based question and answer data from interactions with ChatGPT, were gathered. Following the implementation, semi-structured interviews were conducted with the researcher and participants to discuss details of the lesson design and execution.

Fourth, data analysis was conducted in line with the research questions. The Technology Integration Assessment Rubric (TIAR) was used to evaluate aspects such as curricular objectives, instructional methods and strategies, the functionality of ChatGPT, and the suitability of its application (Harris et al., 2010; Lee & Zhai, 2024). The interview data with pre-service teachers was analysed inductively using keyword analysis within the framework of qualitative text analysis (Kuchartz, 2019), identifying the advantages and considerations in ChatGPT use. Additionally, students' AI literacy was assessed through the four dimensions of the AI literacy analysis framework (Ng et al., 2024a). Finally, the researcher employed a member-checking process to ensure the reliability of the data analysis, leading to the interpretation of the results and formulation of conclusions.

Participants

This study was conducted in the Department of Earth Science Education at a College of Education in a non-metropolitan university in South Korea. Three pre-service teachers (2 females, 1 male) participated in both the design and presentation of an Earth Science simulation lesson using ChatGPT. For confidentiality, pseudonyms were assigned to all participants.

The pre-service teachers had previously completed a range of courses in their major, including introduction to Earth Science, Petrology, Structural Geology, Atmospheric Dynamics, Oceanography, and Astronomy. They had taken specialized courses in Earth Science Education,

such as Earth Science Education Theory, Earth Science Materials and Research Methods, Teaching Practice and Instructional Materials Theory.

Data collection

Data collection in this study was divided into three main stages. First, all materials prepared by the pre-service teachers during the lesson design process were gathered. Specifically, to integrate GenAI into their simulation lessons, the pre-service teachers prepared for various aspects of the lesson, including learning objectives, instructional models, teaching strategies, and assessment methods. This stage involved collecting all written materials, such as lesson plans, instructional resources, and activity sheets. Second, the simulation lessons conducted by the pre-service teachers were recorded through video and audio. Written documentation of the interactions between the pre-service teachers and ChatGPT during the simulation lessons was collected. Finally, after the simulation lesson, self-assessment documents completed by the pre-service teachers were collected. Audio recording of semi-structed interviews between the pre-service teacher and researcher were also obtained.

Evaluation rubric

The Technology Integration Assessment Rubric (TIAR) used in this study to analyse the simulation lesson plans incorporating ChatGPT consists of the following components: curricular objectives, instructional methods and strategies, ChatGPT function selection, and overall appropriateness (Harris et al., 2010; Lee & Zhai, 2024). Specifically, table 1 presents a tool designed to evaluate the effectiveness with which pre-service teachers integrated ChatGPT into their science lesson plan. This rubric assesses how ChatGPT supports each area, focusing on educational objectives, instructional strategies, function selection, and appropriateness. Each criterion is rated on a four-point scale, where a score of 4 indicates strong alignment or optimal use, while a score of 1 indicates misalignment or inappropriate use. By employing this rubric, researchers can systematically assess the extent to which pre-service teachers effectively incorporated ChatGPT to support instructional goals and teaching strategies in their lesson plans. The scores generated form this rubric provide insights into how effectively the pre-service teachers utilized ChatGPT in science education, allowing the researchers to identify their strengths and areas for improvement.

Table 1

The Technology Integration Assessment Rubric (TIAR) based rubric to assess ChatGPT-integrated science lesson

	Item	4	3	2	1
1	**Curriculum goals**	ChatGPT used in the instructional plan are strongly aligned with one or more curriculum goals.	ChatGPT used in the instructional plan are aligned with one or more curriculum goals.	ChatGPT used in the instructional plan are partially aligned with one or more curriculum goals.	ChatGPT used in the instructional plan are not aligned with one or more curriculum goals.
2	**Instructional methods/ strategies**	ChatGPT use optimally supports instructional methods/strategies.	ChatGPT use supports instructional methods/strategies.	ChatGPT use minimally supports instructional methods/strategies.	ChatGPT use does not support instructional methods/strategies.
3	**Function selection(s)**	ChatGPT functional selections(s) are exemplary, given curriculum goal(s) and instructional methods/strategies.	ChatGPT function selections(s) are appropriate, but not exemplary, given curriculum goal(s) and instructional methods/strategies.	ChatGPT function selection(s) are marginally appropriate, given curriculum goal(s) and instructional methods/strategies.	ChatGPT function selection(s) are inappropriate, given curriculum goal(s) and instructional methods/strategies.
4	**'Fit'**	Content, instructional methods/strategies and ChatGPT function fit together strongly within the instructional plan.	Content, instructional methods/strategies and ChatGPT function fit together within the instructional plan.	Content, instructional methods/ strategies and ChatGPT function fit together somewhat within the instructional plan.	Content, instructional methods/strategies and ChatGPT function do not fit together within the instructional plan.

Semi-structured interviews

The semi-structured interview protocol was designed to gain empirical insights into the advantages and considerations of using ChatGPT, as well as to understand the planning and implementation of the simulation lessons (Table 2). The protocol included questions on the perceived benefits and drawbacks of using ChatGPT in simulation lessons, considerations noted by pre-service teachers, reasons for selecting specific instructional models, questions on the integration of subject content, methods for assessing achievement of learning objectives, and differences between lesson utilizing ChatGPT and Those that do not. This interview allowed pre-service teachers to reflect on their simulation lessons as a formative opportunity, enabling them to self-assess their lesson planning and practical approaches.

Table 2

Semi-structured interview protocol

	Question Categories	Semi-structured questions
1	Advantages of Using ChatGPT in Simulated Earth Science Lessons	(Mandatory) What did you find advantageous about using ChatGPT in the lesson?
2	Disadvantages of Using ChatGPT in Simulated Earth Science Lessons	(Mandatory) What challenges or disadvantages did you encounter when using ChatGPT?
3	Precautions When Using ChatGPT	(Mandatory) What aspects did you pay particular attention to when using ChatGPT in the lesson?
4	Comparison Between Lessons Using ChatGPT and Those Without	(Mandatory) What do you think are the main differences between lessons that use ChatGPT and those that do not? Please explain why you think so.
5	Future Possibilities for ChatGPT Utilization	(Mandatory) Do you think ChatGPT could be used in lessons beyond your simulated lesson topic?
6	Reflection on Simulated Lessons and Additional Questions	(Optional) Could you reflect on why you chose this lesson model, its suitability with ChatGPT, and how you ensured the lesson objectives were met?

Data analysis

Data analysis was conducted in three steps, each aligned with the research questions. For the first research question regarding the scope of ChatGPT's application in Earth Science lessons, analysis was conducted using TIAR, which focuses on instructional objectives, models, strategies, ChatGPT functions, and appropriateness. The rubric operates on a four-point scale and was applied to the lesson plans and all instructional materials created by pre-service teachers.

For the second research questions, which explored the advantages and considerations of ChatGPT use in science instruction, semi-structured interviews were transcribed, and written documentation of the interactions with ChatGPT was collected and inductively interpreted. The third research question explored the relevance of GenAI science lessons to learners' AI literacy using the AI Literacy Framework (Ng et al., 2024a), which includes four dimensions: affective, behavioural, cognitive, and ethical. Data were collected from lesson materials, recordings, and semi-structured interviews. The analysis coded data to identify how ChatGPT influenced learning across these dimensions. Affective aspects, such as motivation and confidence, emerged from semi-structured interviews. Behavioural aspects were observed in group activities during lessons, showcasing collaborative engagement with AI tools. Cognitive elements were assessed through students' use of ChatGPT for understanding and applying scientific concepts. Ethical considerations focused on discussions around data privacy and AI biases in lesson recordings. This approach directly linked the analysis to the research question, providing insights into ChatGPT's impact on learners' AI literacy.

To ensure the reliability and validity of the data analysis, the researcher employed multiple strategies to verify the findings. First, preliminary results were presented at two Geoscience Education conferences in Korea to gather feedback and refine the analysis. While quantitative data were not included in this study, various aspects of the qualitative data were explored in depth to establish foundation for the study's conclusions. To ensure content validity, multiple stages of peer review were conducted. An in-person review was held with a faculty member specializing in Geoscience Education to discuss the research design, analysis methods, and interpretation of results. Following the semi-structured interviews, qualitative data were coded by themes to extract key topics. A second in-person review with the same faculty member was conducted to verify the researcher's interpretations and ensure alignment with the data. Finally, the results and conclusions were reviewed by an Earth Science educator holding a doctoral degree. Through iterative discussions, the consistency of the interpretations was evaluated, and any differences in opinion were resolved through additional Zoom meetings. These processes contributed to enhancing the reliability of the study's findings.

Results

Earth science simulation lessons using ChatGPT (RQ1)

Instrumental aspects refer to the ways in which ChatGPT serves as a tool for enhancing or facilitating the Earth Science simulation lessons. It emphasizes ChatGPT's role as a practical resource that can be applied in various instructional capacities essentially, the tool like qualities or practical applications of ChatGPT that make it useful in teaching. By highlighting the instrumental aspects, the title suggests a focus on exploring how ChatGPT can be utilized effectively within lesson plans, strategies, and instructional methods, acting as a resource to support specific teaching and learning objectives in Earth Science education.

The first research question focused on how pre-service teachers could utilize ChatGPT in Earth Science simulation lessons. Specifically, four pre-service teachers who are Yuran, Juyeong, and Giwon were evaluated using the TIAR, which examines curricular objectives, instructional models and strategies, ChatGPT functionality, and overall appropriateness. Each case received a score based on the alignment of the lesson objectives, integration of ChatGPT within the instructional strategy, selection of ChatGPT features, and overall fit. These scores allowed for an analysis of how ChatGPT was applied in each case, along with its effectiveness and areas for improvement (Table 3).

Table 3

Pre-service Teacher's TIAR Score

	Curriculum goals	Instructional methods/ strategies	Function selection(s)	'Fit'	Overall (average)
Yuran	4	3	3	3	3.25 / 4
Juyeong	4	4	3	3	3.5 / 4
Giwon	4	4	3	3	3.5 / 4

Yuran's Case

This lesson, designed for high school Earth Science, focused on methods for measuring astronomical distances. ChatGPT was used to explore complex astronomical concepts. The alignment between curriculum goals and ChatGPT usage was strong, earning a score of 4-point. Students learned about parallax and Cepheid variable start, with ChatGPT helping to explain these concepts and facilitate understanding. As such, ChatGPT was deemed effective in helping students achieve learning objectives. In terms of instructional strategies and ChatGPT use, the lesson scored a 3-point. The POE(Prediction-Observation-Explanation) model was employed, with students using ChatGPT to explore methods for measuring astronomical distances and sharing information within groups. However, while ChatGPT supported the inquiry process, there was room for improvement in its integration with the lesson's core inquiry activities. ChatGPT was primarily used as a tool for information retrieval rather than as a dynamic component of exploration or discussion. More interactive features, such as real-time question-answering or simulations of the distance-measuring process, could have enhanced student engagement.

In the selection of ChatGPT functions, Yuran's lesson also scored a 3-point. Although ChatGPT effectively provided explanations and assisted students in understanding scientific concept, it lacked visual aids or simulations. Students learned about parallax and the period-luminosity relationship of Cepheid stars, but the absence of visual or interactive tools limited their ability to analyse data directly. Notwithstanding ChatGPT had been able to present visual representations or enable simulations, students' comprehension might have deepened. In the appropriateness category, a score of 3-point was awarded. ChatGPT was well-integrated with the lesson objectives, allowing students to grasp complex astrophysical concepts and apply them too problem-solving. Overall, while the lesson successfully incorporated ChatGPT, the lack of more sophisticated features, such as real-time simulations, was a drawback.

Juyeong's Case

This lesson addressed the interaction between the atmosphere and oceans, particularly focusing on the causes of El Niño and La Niña, and their impacts on climate. Juyeong's lesson earned a score of 4-point for both curriculum objectives and ChatGPT use. ChatGPT facilitated students' understanding of climate change by simplifying complex concepts and explaining the causes and effects of climatic phenomena. In instructional strategies and ChatGPT use, Juyeong's lesson also scored a 4-point. Students worked collaboratively to explore El Niño and La Niña, with ChatGPT serving as an effective tool for researching and sharing information. The tool supported both cooperative and inquiry-based learning models effectively.

In the functionality category, the lesson scored a 3-point. While ChatGPT provided relevant information, it did not utilize real-time climate data or visual simulations, which would have enabled more in-depth exploration. These additional features could have enriched students' understanding of climate variations and enhanced the overall learning experience. In the appropriateness category, Juyeong's lesson received a 3-point. ChatGPT was highly compatible with the lesson's goals, assisting students in understanding complex climate concepts and facilitating presentations. There were some areas where the use of simulation features related to climate change could have been further enhanced. Overall, the lesson effectively leveraged ChatGPT, though the inclusion of data analysis and visual simulation capabilities could have provided a more comprehensive learning experience.

Giwon's Case

Giwon's lesson focused on the formation and movement of typhoons, with ChatGPT supporting scientific inquiry and prediction. The lesson received a score of 4-point in both curriculum objectives and ChatGPT use, as ChatGPT facilitated students' understanding of typhoon formation, structure, and tracking, helping them achieve their learning objectives. In instructional strategies and ChatGPT use, Giwon's lesson also scored a 4-point. The lesson, based on the POE(Prediction-Observation-Explanation) model, utilized ChatGPT to analyse typhoon paths and make predictions. ChatGPT's real-time data integration was suitable for this inquiry-based activity.

For functionality, the lesson received a 3-point. ChatGPT was used to analyse typhoon trajectories, but issues with real-time data accuracy and discrepancies between predicted and actual paths were noted. Addressing these limitations could have made the lesson more reliable and engaging. In the appropriateness category, the lesson scored a 3-point, with ChatGPT fitting well with the lesson content and strategies. Overall, Giwon's lesson effectively integrated ChatGPT, allowing students to explore typhoons using real data. However, a deeper focus on data reliability and comparison with actual paths could have enhanced the experience. Across all three cases, ChatGPT was instrumental in supporting learning objectives and aiding students in exploring complex concepts. However, the absence of real-time simulations and visual aids was a consistent limitation. While ChatGPT effectively aligned with lesson objectives and instructional strategies, further enhancements in functionality could deepen student learning experiences and engagement.

Balancing convenience and challenges of ChatGPT in earth science simulations (RQ2)

The second research question focused on analysing pre-service teachers' responses regarding the advantages and considerations of using ChatGPT in Earth Science simulation lessons. Responses were interpreted inductively by identifying common themes from the semi-structured interview transcripts (Table 4). The analysis prioritized shared responses regarding ChatGPT's benefits and limitations, while reflections on the simulation lessons and follow-up questions were addressed optionally during individual interviews. From the semi-structured interviews, it emerged that pre-service teachers perceived ChatGPT as a versatile tool with various applications in lessons. Respondents noted that ChatGPT facilitated more flexible and efficient lesson delivery, fostering student engagement and promoting scientific thinking. The teachers provided examples from both astronomy and meteorology lessons, illustrating ChatGPT's potential as a practical tool in educational settings. A major advantage highlighted by the pre-service teachers was ChatGPT's ability to provide students with immediate access to various resources. For instance, one teacher-in-training described a lesson on Cepheid variable stars, where ChatGPT provided data on the period-luminosity relationship, enabling students to calculate stellar distances. This immediate access to complex information allowed smoother interaction between teachers and students, helping students comprehend challenging scientific concepts more easily.

Table 4

Results of pre-service teachers' question and responses on the use of ChatGPT in simulated Earth Science lessons.

	Question Categories	Inductive Interpretation
1	Advantages of Using ChatGPT in Simulated Earth Science Lessons	It is expected that using ChatGPT to search for and provide various resources, as well as allowing students to ask individual questions freely, will have a positive impact on students' science learning outcomes.
2	Disadvantages of Using ChatGPT in Simulated Earth Science Lessons	When using ChatGPT for questions and answers, there are times when it may provide inaccurate information or incorrect resources, making it essential for teachers to verify the content.
3	Precautions When Using ChatGPT	When real-time data analysis and interpretation are required based on information that is difficult to observe directly, it is important to develop the ability to evaluate the data provided by ChatGPT. Learners should be cautious not to trust ChatGPT blindly and should consider verifying information sources and reflecting on other ethical issues.
4	Comparison Between Lessons Using ChatGPT and Those Without	Compared to traditional classes in the past, the differences in science lessons utilizing ChatGPT include the ability to analyse data based on observational information rather than substituting with simulations or videos, the flexibility for students to engage in Q&A on scientific concepts according to their level, and the continuous provision of high-quality assessments.
5	Future Possibilities for ChatGPT Utilization	Based on the lesson examples from other pre-service teachers, it appears that the potential for utilizing ChatGPT in Earth Science education has been effectively demonstrated.
6	Reflection on Simulated Lessons and Additional Questions	Deep consideration and effort are needed regarding how to specifically use ChatGPT in lessons. For instance, it is important to practice interpreting meteorological data or astronomical observation data, reflect on these tasks, and experience concrete examples such as verifying the sources of observational data. Other pre-service teachers also emphasize the necessity of instructional experiences that incorporate ChatGPT.

In meteorology, ChatGPT proved particularly useful. Another pre-service teacher described using ChatGPT in a lesson on typhoon formation and movement, where students accessed real-time weather data and analysed typhoon trajectories. For example, students used ChatGPT to view recent satellite images and weather records, which helped them analyse and hypothesize the dangerous and safe sides of a typhoon. The real-time data provision allowed students to interact directly with meteorological information, thereby enhancing engagement and grounding the lesson in real-world applications. However, limitations of ChatGPT were also identified. Pre-service teachers noted that ChatGPT sometimes provided inaccurate or incomplete information, which required careful verification. For example, in an astronomy lesson, some of the data on celestial objects did not align with current observations, or the sources were unclear. In

meteorology lessons, real-time data could occasionally be outdated or differ from actual typhoon paths. To address this, teachers emphasized the need for careful vetting of ChatGPT-provided information and the importance of instilling critical thinking skills in students.

One crucial consideration when using ChatGPT in lessons is ensuring that students do not accept information uncritically. Pre-service teachers suggested that it is essential to teach students to verify sources and consider the ethical implications of the data provided by ChatGPT. Specifically, when using real-time data such as weather or astronomical observations, the source and accuracy of the information should be scrutinized. The teachers recommended instructing students on methods for assessing the reliability of ChatGPT-generated content to reinforce critical thinking. Comparing lessons with and without ChatGPT, pre-service teachers noted that lessons incorporating ChatGPT allowed for more self-directed learning, as students could freely ask questions and receive immediate answers. For example, in a meteorology lesson on typhoon movement, students received real-time weather data through ChatGPT and conducted independent analyses. This interactive learning environment deepened students' understanding of natural phenomena. In contrast, traditional lessons often relied on predetermined textbooks or materials, making it more challenging for students to ask questions or receive immediate feedback tailored to their learning levels.

Additionally, ChatGPT was useful in assessing whether learning objectives were achieved. Pre-service teachers used ChatGPT to facilitate assignments where students utilized the information to complete tasks, followed by presentations and discussions to verify their understanding. In a lesson on typhoon formation, for instance, students validated their predictions based on actual weather data, thereby clarifying learning objectives and enhancing the lesson's effectiveness. Finally, pre-service teachers discussed the potential for broader applications of ChatGPT across various subjects. They noted the value of ChatGPT's real-time data provision and analysis capabilities in meteorology lessons, suggesting that these features could help make scientific inquiry more immersive. The teachers also proposed collaborating with other educators to develop strategies for using ChatGPT effectively in the classroom. The interview results indicate that ChatGPT holds significant potential for Earth Science education. In subjects ranging from astronomy to meteorology, ChatGPT can serve as a valuable tool for providing real-time information, supporting analysis, and enhancing student engagement. However, to maximize its effectiveness, it is essential to verify data reliability, foster critical thinking, and address ethical considerations.

Exploring the impacts of ChatGPT on learners' AI literacy (RQ3)

The third research question explored the potential impacts of ChatGPT-enhanced Earth Science lessons on learners' AI literacy using the AI Literacy Framework (Ng et al., 2024a). This framework encompasses four dimensions: affective, behavioural, cognitive, and ethical. Analysing lesson materials, lesson recordings, and post-lesson interviews, each of the four dimensions was examined to assess how ChatGPT influenced the AI literacy of the participating pre-service teachers. This study offers concrete examples of how AI literacy may be embedded into Earth Science lessons, representing an early approach to understanding this integration. This research question examined how ChatGPT use influenced learners' AI literacy, analysing the four domains of AI literacy: affective, behavioural, cognitive, and ethical (Ng et al., 2024a). Using simulation

lesson examples from three pre-service teachers who are Yuran, Juyeong, and Giwon, the study evaluated the impact of ChatGPT on each dimension, with specific attention to cognitive learning subcategories such as understanding, application, and evaluation.

Affective domain

The affective dimension of AI literacy involves students' motivation and confidence during the learning process. ChatGPT appeared to positively influence this area. For instance, in Yuran's astronomy lesson, students used ChatGPT to explore concepts like parallax and Cepheid variables, which bolstered their confidence in learning and heightened their motivation. In Juyeong's climate change lesson, ChatGPT helped students understand El Niño and La Niña, fostering engagement as they analysed scientific data. Similarly, in Giwon's typhoon lesson, ChatGPT provided rea-time meteorological data, enabling students to predict typhoon paths and boosting their confidence in their predictive abilities.

Behavioural domain

In terms of the behavioural domain, ChatGPT facilitated active participation and collaborative learning among students. For example, in Giwon's typhoon lesson, students worked in groups to predict typhoon trajectories using real-time data provided by ChatGPT, strengthening collaborative learning. Yuran and Juyeong's lessons also encouraged students to collaboratively explore complex scientific concepts, supporting the development of behavioural competencies aligned with AI literacy by promoting teamwork and active engagement with AI tools.

Cognitive domain

The cognitive domain is divided into three subcategories: knowing and understanding AI, using and applying AI, and evaluating and creating AI (Ng et al., 2024a). In Yuran's astronomy lesson, students were introduced to ChatGPT and instructed on its functionality. ChatGPT was used to explain parallax and Cepheid variables, helping students understand these astronomical concepts. Students then applied their learning to solve problems involving parallax calculations, demonstrating a progression from understanding to application. Giwon's lesson took this further by having students analyse real-time typhoon data to predict future movements, addressing the need for disaster preparedness. This activity involved not only understanding and applying AI but also evaluating and creating by comparing predicted paths with actual data to assess accuracy. Through these activities, Giwon's lesson engaged with all three stages of cognitive learning, including evaluating the reliability of the data.

Ethical domain

The ethical domain pertains to the responsible use of AI technology and an understanding of its societal implications (Ng et al., 2024a). In Giwon's lesson on typhoons, ChatGPT facilitated discussions on responsible AI use as students analysed weather data to predict natural disasters. This process encouraged students to consider the reliability and ethical implications of AI-generated data, such as potential biases in ChatGPT's responses and the importance of data privacy. While other lessons also touched on ethical considerations, Giwon's lesson emphasized this aspect more than others by exploring these topics in depth, particularly in the context of disaster prediction and data verification.

In conclusion, this study demonstrates that simulation lessons utilising ChatGPT have the potential to address all dimensions of AI literacy. As a tool for exploring AI literacy, ChatGPT is

expected to enhance its utility in Earth Science education by providing real-time data analysis and encouraging considerations of data provenance, accuracy, and transparency. Moreover, ChatGPT can contribute to increasing students' motivation and confidence by offering personalized feedback and fostering a sense of autonomy in the learning process. Through its interactive features, ChatGPT enables students to explore scientific concepts at their own pace, allowing them to engage more deeply with the material and develop a stronger sense of ownership over their learning. However, this study acknowledges a limitation in the lack of quantitative assessment of the nuanced aspects of AI literacy. Despite this limitation, the research highlights ChatGPT's potential as an educational tool for fostering comprehensive AI literacy, including critical thinking and ethical awareness, within the context of scientific inquiry.

Discussion

In this study, pre-service teachers seemed to emphasize the instrumental aspects of utilizing GenAI for instructional implementation, suggesting its role as a potentially practical tool in teaching and learning. Moreover, one of the possible advantages of simulation lessons incorporating GenAI might be their potential to positively influence learners' development of AI literacy in the future (Casal-Otero et al., 2023; Yim & Su, 2024). However, a key limitation of this study lies in the small number of cases included. This limitation constrains the generalizability of the findings and highlights the need for further studies involving larger sample sizes. A broader dataset would allow for deeper insights into how GenAI can be systematically integrated into diverse educational contexts, providing more robust and reliable conclusions. Addressing this limitation in future research could significantly enhance the understanding of GenAI's role in education (Burke & Crompton, 2024).

The first recommendation from this study is the need for education that encourages the more active use of ChatGPT’s advanced features. ChatGPT’s functionalities, such as simulations and real-time data analysis, can greatly enhance the learning process. By integrating these features, students could engage in more in-depth learning experiences and gain a more intuitive understanding of scientific concepts. For instance, when measuring astronomical distances, if ChatGPT provided visual aids or simulations, students could achieve a clearer and more comprehensive learning experience in this study. In pre-service teacher training, additional education on constructing simulation scenarios and leveraging these tools effectively, alongside basic GenAI usage, would enable pre-service teachers to utilize ChatGPT’s advanced features to create more enriched learning environments and demonstrate greater instructional expertise (Okulu & Muslu, 2024). Another key recommendation is to emphasize the development of critical thinking skills in lessons that incorporate ChatGPT. While ChatGPT provides access to vast amounts of information, the accuracy and reliability of this information are not always guaranteed (Adel et al., 2024). Therefore, students should be equipped with the ability to critically analyse and verify the information they receive from ChatGPT, rather than accepting it uncritically. Pre-service teachers should instruct students on how to assess and validate the data provided by GenAI, guiding them on ways to use AI tools with a critical mindset. Through this approach, students can cultivate an ethical and critical attitude toward the use of GenAI information.

In terms of higher education, incorporating GenAI into science education offers unique opportunities to transform traditional teaching methods. For example, the ability to simulate

complex scientific phenomena in real-time could enable students to engage more actively in inquiry-based learning (Ng et al., 2024b). Such approaches not only enhance conceptual understanding but also foster skills essential for modern scientific exploration, including problem-solving and data interpretation (Wang et al., 2024; Zhai et al., 2024). These innovations align with the growing emphasis on learner-centered education in higher education settings, suggesting a need for further development of tailored pedagogical frameworks (Airaj, 2024).

Future research could further investigate how specific features of ChatGPT, such as visual simulations and real-time data analysis, can support inquiry-based learning activities. Additionally, studies could examine the impact of these advanced functionalities on students' scientific inquiry skills and how they contribute to fostering a deeper understanding of complex concepts (Kilinc, 2023). Developing educational strategies that help students critically evaluate the reliability of information provided by ChatGPT would also be a valuable direction. Such research could pave the way for ChatGPT to be used as an effective and ethical tool for learner-centered scientific inquiry, demonstrating its potential to support students in both scientific exploration and critical evaluation in educational settings (Wang et al., 2024). Lastly, while this study highlights the promising potential of GenAI in educational settings, future work should strive to explore its application across various disciplines and learning environments. For instance, interdisciplinary approaches that integrate GenAI into subjects beyond science, such as social sciences or humanities, could provide new insights into its versatility and effectiveness (Burke, & Crompton, 2024). Additionally, longitudinal studies examining the long-term effects of GenAI on students' AI literacy and critical thinking skills would help solidify its role as a transformative tool in education. By addressing these aspects, future research could contribute to building a more comprehensive framework for the ethical and effective use of GenAI in higher education.

Conclusion

This study explores the practical characteristics of Earth Science simulation lessons utilizing ChatGPT. Specifically, the study examined how pre-service Earth Science teachers planned and incorporated ChatGPT into their lessons, with a focus on achieving educational objectives, employing effective instructional strategies, and ensuring overall appropriateness. The findings indicated that ChatGPT was a valuable tool for facilitating students' understanding of complex scientific concepts in areas such as astronomy, meteorology, and mineralogy. The three participating pre-service teachers who are Yuran, Juyoeng, and Giwon, demonstrated that ChatGPT could effectively help meet learning objectives and foster a more interactive learning environment where students could ask questions and receive real-time feedback. However, limitations were also observed, as only certain ChatGPT features were utilized, and visual aids or simulation functionalities that could deepen the learning experience were not incorporated. This study presents three main conclusions. First, ChatGPT was confirmed to be a useful tool for helping pre-service teachers achieve the educational objectives of Earth Science simulation lessons. In each case, the pre-service teachers used ChatGPT to assist students in comprehending challenging scientific concepts. For instance, during an astronomy lesson, ChatGPT was employed to explain the concepts of parallax and Cepheid variable stars, which helped students understand how to measure astronomical distances. This suggests that ChatGPT can serve as an effective resource for clarifying complex concepts, making it a valuable aid for learners encountering difficult scientific topics.

Second, ChatGPT has the potential to enhance lesson interactivity and increase student engagement. For example, in a lesson on typhoons, ChatGPT provided real-time meteorological data, which enabled students to actively participate in predicting the path of a typhoon. This type of interactive approach allowed students to engage with the material directly, rather than passively listening to explanations. By exploring and analysing data on their own, students were encouraged to immerse themselves in scientific inquiry, thereby benefiting from a more active and participatory learning experience. This interactivity shows ChatGPT's potential to create a learning environment that supports greater engagement and collaboration. Third, while ChatGPT proved effective in providing information and explanations, its limited use of visual and simulation features posed a notable drawback. For example, in the astronomy lesson, visualizing the process of measuring celestial distances or simulating parallax calculations could have further enhanced students' understanding. Notwithstanding pre-service teachers had incorporated these additional features, ChatGPT could have provided a richer exploratory learning experience. The absence of these elements highlights an opportunity for improvement, as integrating advanced functionalities such as visual aids and simulations could support deeper conceptual understanding and provide students with a more comprehensive and interactive approach to learning science. Lastly, ChatGPT has demonstrated significant potential as an instructional tool in Earth Science education. Its ability to support educational objectives, foster interactivity, and enhance student engagement suggests that it can play a valuable role in helping students grasp challenging scientific concepts. However, to maximize ChatGPT's educational effectiveness, pre-service teachers should consider expanding its use to include visual and simulation functionalities.

Conflict of Interest

The author(s) disclose that they have no actual or perceived conflicts of interest. The authors disclose that they have not received any funding for this manuscript beyond resourcing for academic time at their respective university. This study was approved by the Institutional Review Board (IRB) of the university affiliated with the researcher. No AI tools were used in the writing of this paper.

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