The efficacy of selected approaches in teaching Earth Science among Grade 11 students

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ABSTRACT

This study investigated the effectiveness of Project-Based Learning (PBL), Technology-Based Learning (TBL), and Contextualized-Based Learning (CBL) in teaching Earth Science to Grade 11 STEM students at Cabadbaran City National High School. Using a one-group pretest-posttest quasi-experimental design, the research involved 115 purposively selected students. Data were collected via a standardized survey and analyzed using Mean Percentage Score (MPS), Paired-Sample t-test, and ANOVA. Pretest results revealed a "Nearly Proficient" (60% MPS) understanding, with the lowest performance in "Describing the structure and evolution of ocean basins" (44%), indicating gaps in prior knowledge. Posttest results showed significant improvement, with students reaching "Highly Proficient" levels (TBL: 93%, PBL: 90%, CBL: 89%). Statistical analysis confirmed significant differences (p = 0.000) between pretest and posttest scores, rejecting the null hypothesis. However, metamorphism, magma formation, and plate tectonics remained challenging across all approaches. The study concludes that PBL, TBL, and CBL effectively enhance Earth Science comprehension, with TBL yielding the highest gains. To support instruction, a structured Daily Lesson Log integrating these approaches was proposed, emphasizing student-centered, technology-enhanced, and real-world applications for improved learning outcomes.

Keywords: project-based learning (PBL), technology-enhanced instruction, Earth Science education

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INTRODUCTION

Developing a strong knowledge of Earth Science is now essential as the Earth confronts growing environmental challenges, including climate change, declining biodiversity, and the urgent necessity for sustainable living. According to UNESCO (2023), providing students with the necessary knowledge and skills to analyze and respond to these challenges is key to fostering informed decisions and nurturing responsible global citizens.

Moreover, Landicho (2021) investigated that with the fast-paced progress in science and technology, cultivating a scientifically literate population who can think critically, solve problems, and make informed choices is more important than ever. Key to reaching this objective is Earth Science, which is taught in senior high school and helps students grasp Earth's systems, the forces sculpting our world, and the interdependence of all species. Teaching this changing field well still presents difficulties, even with its significance. Conventional approaches stressing memory and passive learning can fail to involve pupils or promote significant knowledge. In a world where digital media and knowledge surround students, it is imperative to use creative and engaging teaching techniques that pique interest in science and create a lifetime passion.

Additionally, Cabadbaran City National High School, a mega-school serving a diverse student population, faces the unique challenges inherent in large educational institutions. These include managing large class sizes, catering to different strands of TVL (SMAW, BPP, Cookery, and Home Economics) and Academics Strand (STEM, HUMSS, ABM, and GAS). Although the institution aims to deliver high-quality education, 2,471 total students might sometimes make it challenging to apply tailored instruction and satisfy the specific needs of every student.

Moreover, it is always a challenge to keep up with the most recent developments in educational technology and properly include them in the course of study. At Cabadbaran City National High School, 68 teachers, one master teacher, and one principal routinely struggle with applying ideas to real-world situations, analyzing challenging data, and doing scientific research. This difference between theoretical knowledge and practical application emphasizes the importance of investigating and using more successful teaching strategies.

This study sought to close this void by looking at the efficacy of selected teaching approaches, Project-Based Learning (PBL), Technology-Based Learning, and Contextualized-Based Learning in teaching Earth and Life Science to Grade 11 students at Cabadbaran City National High School. These strategies were selected because they presented viable means to include students in active learning, promote more knowledge, and acquire necessary 21st-century skills. Through practical projects, PBL urged students to investigate real-world challenges, fostering critical thinking and teamwork. Technology-based learning produced interactive and interesting learning environments by leveraging digital tools and resources. Contextualized-based learning made learning more relevant and meaningful by tying scientific ideas to the experiences and lives of students. This study aimed to give insightful analysis for teachers at Cabadbaran City National High School and beyond by contrasting the efficiency of these approaches to conventional methods, thus helping to improve science education and produce scientifically literate people.

Moreover, there was a scarcity of research exploring the long-term effects of selected teaching approaches, specifically how they influenced students' knowledge retention over time, attitudes toward science, and potential pursuit of future academic studies or careers in this domain. Understanding the lasting effect of Project-Based Learning (PBL), Technology-Based Learning, and Contextualized-Based Learning was vital to determine its true potential in cultivating lifelong learning and scientific literacy in Earth Science. This study addressed these gaps by determining the efficacy of selected teaching approaches in fostering a deep understanding of Earth Science concepts among Grade 11 students. It looked at how different chosen teaching strategies—such as cooperative projects, inquiry-based investigations, real-world problem-solving scenarios, designing and running experiments, and model creation—affected students' learning results, critical thinking skills, and scientific inquiry abilities. This study looked at how PBL can enable students to deepen their grasp of difficult Earth Science ideas by immersing them in real-world, hands-on projects reflecting actual scientific efforts.

This study also looked at the effectiveness of Project-Based Learning (PBL), Technology-Based Learning, and Contextualized-Based Learning on student motivation, engagement, and attitudes toward Earth Science, determining whether this method encouraged greater respect for the subject matter and want for ongoing learning in this field. The results of this study gave important new perspectives for educators seeking to implement effective selected teaching approaches and strategies in their classrooms and contributed to the development of innovative curricula and instructional materials that promoted student-centered learning in this crucial scientific domain.

This study had significant implications for the field of education, particularly in Earth Science instruction. Provide insightful analysis of how well particular teaching strategies might promote deep understanding and improve student involvement among Grade 11 students, thus helping to foster scientific literacy and equip future generations for the opportunities and challenges presented by our fast-changing environment. The findings of this study could direct pedagogical approaches, instructional design, and curriculum development, so improving the learning environment for students in this crucial field by means of their successful involvement. A key output of this study was the development of lesson plans for each teaching approach, along with a training design outlining how to cascade these approaches in science teaching.

Furthermore, by analyzing the effects of particular teaching strategies on knowledge retention, attitudes toward science, and possible career paths, this study aimed to clarify the ongoing relevance of this method in forming students' lifetime learning paths and enabling them to become informed and responsible citizens in a world growingly linked and complex.

Research objectives

The study determined the efficacy of project-based learning, technology-based learning, and contextualized-based learning approaches in enhancing the conceptual understanding of Earth Science among Grade 11 students.

Specifically, this research sought to answer the following questions:

1. What are the pretest scores of the Grade 11 students before the implementation of Project-Based Learning, Technology-Based Learning, and Contextualized-Based Learning?
2. After the pretest, what are the identified least learned competencies?
3. What are the posttest scores of the Grade 11 students after the implementation of Project-Based Learning, Technology-Based Learning, and Contextualized-Based Learning?
4. Is there a significant difference in the scores of the Grade 11 students before and after the implementation of the approaches?
5. Based on the posttest results, what are the identified least learned competencies after the implementation of Project-Based Learning, Technology-Based Learning, and Contextualized-Based Learning?
6. Based on the findings of the study, what plan of action can be designed?

METHODOLOGY

This Chapter presents the research design, locale, respondents and sampling, research instrument, ethical considerations, data gathering procedure, and statistical treatment.

This study utilized a one-group pretest-posttest quasi-experimental design to determine the efficacy of selected teaching approaches Project-Based Learning, Technology-Based Learning, and Contextualized-Based Learning in teaching Earth Science to Grade 11 students. This design was appropriate because it allowed for the comparison of the same group of students' performance before and after the implementation of the PBL, TBL, and CBL approaches. Three classrooms, Galilei, Mendeleev, and Pythagoras sections, were assigned to each of the three learning approaches, respectively. This design was appropriate because it allowed for the comparison of learning outcomes across different teaching methodologies in relatively naturalistic educational settings.

This study involved all Grade 11 students enrolled in the STEM strand and taking Earth Science at Cabadbaran City National High School during the 2024–2025 school year. The total number of student respondents was 115, which constituted a census of the Grade 11 STEM students enrolled in Earth Science at the school. The respondents were distributed heterogeneous sections that shared similar academic characteristics. Each section was subjected to a distinct teaching approach—Project-Based Learning, Technology-Based Learning, and Contextualized-Based Learning—allowing for comparative analysis. A purposive sampling technique was employed, as the study focused on this specific and well-defined population.

Cabadbaran City National High School, situated within the South District of the Division of Cabadbaran City, under the jurisdiction of the Department of Education (DepEd), Philippines. This geographical specificity is crucial as it contextualizes the study within a defined educational administrative structure. Cabadbaran City, as a locale, presents a blend of environmental and socio-economic factors that directly influence the learning experience of the STEM Grade 11 students at Cabadbaran City National High School. Being within the Caraga Region, the city experiences diverse geological phenomena, making Earth Science a subject of immediate relevance to the students' lives. The school itself, as a public institution under DepEd, operates within the national curriculum framework, yet it is also subject to local educational policies and resource availability.

This study utilized pretests and posttests as the primary research instrument to gather data. The standardized assessments were adapted from the Department of Education, Division of Cabadbaran City. They were designed for the whole 4th quarter of the second semester school year 2024-2025 and reviewed by the CCNHS-SHS Science Coordinator and approved by the School Principal. The tests consisted of multiple-choice questions meticulously designed to assess Grade 11 students' conceptual understanding of Earth Science topics. Aligned with the DepEd curriculum, the assessments covered key concepts relevant to the study, ensuring that the findings accurately reflected students' grasp of the subject matter. This approach leveraged the established validity and reliability of DepEd's standardized assessments, strengthening the rigor and credibility of the research

The data collection process for this study meticulously assessed the efficacy of three distinct teaching approaches PBL, TBL, and CBL in enhancing Earth Science understanding among STEM Grade 11 students at Cabadbaran City National High School. The process began by obtaining the necessary permissions. The researcher formally requested permission to conduct the study, starting with a letter to the Schools Division Superintendent of the Department of Education division of Cabadbaran City. Upon receiving approval, the researcher sought endorsement from the Public Schools District Supervisor of the south district where the school is located. Finally, a letter was submitted to the principal of Cabadbaran City National High School to obtain permission to conduct the research on school grounds.

Once all necessary permissions were granted, the researcher met with the Grade 11 STEM students taking Earth Science to explain the purpose of the study, the data collection procedures, and emphasized the confidential nature of their participation. Informed consent was obtained from both students and their parents/guardians prior to any data collection activities. To maximize student participation and minimize disruption to classroom instruction, the pretest and posttest were administered during their scheduled homeroom period under the researcher's supervision. This controlled environment ensured focused completion of the assessments. For any students unable to participate during the designated time, alternative arrangements were made, such as offering different time slots or allowing individual completion under the researcher's guidance. Throughout the data collection process, the researcher maintained open communication with students and teachers, promptly addressing any questions or concerns to ensure a smooth, ethical, and efficient data gathering procedure.

Initially, a pretest, constructed by the researcher based on the targeted learning competencies, was administered to each of the three participating sections: Galilei, Mendeleev, and Pythagoras. This pretest, designed to establish a baseline Mean Performance Score (MPS), was checked using the ZipGrade platform, ensuring accuracy and efficiency in scoring. The test questions were developed in alignment with the curriculum standards and underwent a thorough item analysis to validate their reliability and validity.

For the Galilei section, following the pretest, the PBL approach was implemented, engaging students in collaborative, inquiry-driven projects related to Earth Science concepts. Subsequently, a posttest, mirroring the pretest in content, was administered and also checked via ZipGrade.

Similarly, the Mendeleev section underwent a pretest, followed by the implementation of the TBL approach, which integrated technology-based resources and tools to facilitate learning. A posttest was then administered, and the MPS results were compared to evaluate the effectiveness of TBL.

Lastly, the Pythagoras section was subjected to a pretest, followed by the implementation of the CBL approach, which connected Earth Science concepts to students' local environment and lived experiences in Cabadbaran City. A posttest was conducted, and the MPS results were compared to assess the CBL approach's impact.

Throughout all phases of data collection, open communication was maintained with students and teachers to address any concerns promptly. This comprehensive process allowed for a robust evaluation of the efficacy of each teaching approach in enhancing students' conceptual understanding of Earth Science.

This research adhered to the ethical guidelines and principles for data privacy and security mandated by the Philippines' Data Privacy Act of 2012 (Republic Act No. 10173). This law underscored the fundamental right to individual privacy while enabling the responsible use of information for development and innovation. The researcher prioritized transparency by informing participants about how their data would be collected and used. Appropriate security measures were implemented to safeguard all personal data from unauthorized access, misuse, or disclosure. Participants' identities and responses remained strictly confidential and were used solely for the purposes of this research.

The following statistical tools were used to analyze the data.

Mean. It was calculated to determine the average level of conceptual understanding in Earth Science before and after the implementation of the project-based learning, technology-based learning, and contextual-based learning approach.

Standard Deviation. It was computed to measure the variability or spread of the scores around the mean, providing insights into the distribution of student performance.

Paired sample t-Test. It was used to determine if there was a statistically significant difference between the mean scores of the pretest and posttest. This helped to assess the effectiveness of the project-based learning, technology-based learning, and contextualized-based approach in enhancing students' conceptual understanding.

Analysis of Variance (ANOVA). It was employed to determine if there were statistically significant differences in the mean gain of conceptual understanding in Earth Science among students who experienced PBL, TBL, and CBL approaches, in order to assess the relative effectiveness of each approach in promoting conceptual understanding.

FINDINGS AND DISCUSSION

The findings of this study presents a comprehensive analysis of the results obtained from the study examining the effectiveness of Project-Based Learning (PBL), Technology-Based Learning (TBL), and Contextualized-Based Learning (CBL) approaches in teaching Earth Science to Grade 11 STEM students at Cabadbaran City National High School. The findings reveal critical insights into students' initial competency levels, the impact of innovative teaching strategies, and persistent learning challenges that require targeted instructional interventions. Beginning with the pretest assessment, the data showed that students entered the study with a foundational but incomplete understanding of Earth Science concepts, as evidenced by their overall mean percentage score of 60%, which falls under the "Nearly Proficient" classification according to the established proficiency scale. This baseline measurement is particularly significant as it highlights specific areas where students demonstrated varying levels of prior knowledge before exposure to the experimental teaching approaches.

A detailed examination of the pretest scores across the eight learning competencies revealed an interesting pattern of strengths and weaknesses among the participants. The highest pretest score of 67% was recorded for the competency "Explain how seafloor spreads," suggesting that students had relatively better prior knowledge of this particular concept compared to other topics in the Earth Science curriculum. This finding may be attributed to several factors, including previous instructional emphasis on this topic, its inclusion in earlier grade levels, or perhaps the more tangible nature of seafloor spreading concepts that can be effectively demonstrated through diagrams and models. In contrast, the lowest pretest performance was observed in the competency "Describe the structure and evolution of ocean basins," which garnered a concerning mean percentage score of just 44%. This substantial gap in understanding points to potential deficiencies in how geological processes related to ocean formation and development have been traditionally taught, or possibly reflects the abstract nature of these concepts that require sophisticated spatial reasoning skills.

The pretest results further identified two additional competencies where students struggled significantly: "Describe how rocks behave under different types of stress such as compression, pulling apart, and shearing" with a 58% mean score, and "Explain how the movement of plates leads to the formation of folds, faults, trenches, volcanoes, rift valleys, and mountain ranges" at 59%. These findings collectively paint a picture of student difficulties with geological processes that involve dynamic earth systems, mechanical properties of materials, and large-scale tectonic phenomena. The pattern suggests that concepts requiring visualization of subsurface processes or understanding of forces acting over geological timescales present particular challenges for learners. This aligns with existing educational research which has consistently identified earth systems and plate tectonics as conceptually difficult areas for students across various educational contexts.

The identification of these least learned competencies through pretest analysis served as a crucial foundation for implementing targeted instructional interventions using the three experimental approaches. The decision to focus on these specific areas of difficulty allowed for a more nuanced examination of how different teaching methodologies might address persistent learning gaps in Earth Science education. Contemporary research in science education emphasizes the importance of such diagnostic assessment in informing pedagogical strategies, particularly in disciplines like Earth Science that involve complex systems thinking and abstract concepts. The pretest data not only provided baseline measurements but also helped establish the specific conceptual hurdles that needed to be addressed through the PBL, TBL, and CBL implementations.

Following the implementation of the three teaching approaches, posttest results demonstrated significant improvements in student performance across all competencies. The most striking outcome was the overall advancement to "Highly Proficient" levels, with Technology-Based Learning (TBL) emerging as the most effective approach with a 93% mean percentage score, followed closely by Project-Based Learning (PBL) at 90% and Contextualized-Based Learning (CBL) at 89%. These results strongly suggest that all three instructional strategies can substantially enhance student understanding of Earth Science concepts when compared to traditional teaching methods. The superior performance under TBL conditions may be attributed to several factors inherent to technology-enhanced learning environments, including the capacity for interactive visualizations, immediate feedback mechanisms, and adaptive learning pathways that cater to individual student needs.

A closer examination of competency-specific posttest results reveals interesting variations in the effectiveness of each approach. For instance, TBL produced exceptional outcomes in competencies like "Describe how rocks undergo weathering" (95%) and "Explain why the Earth's interior is hot" (96%), suggesting that technological tools may be particularly effective for teaching processes related to surface geology and earth's internal heat mechanisms. The high scores in these areas could reflect the power of digital simulations and virtual laboratories in making invisible processes visible and dynamic earth systems more comprehensible. In contrast, CBL, while still effective overall, showed relative weaknesses in more abstract competencies such as "Describe what happens after magma is formed" (83%) and "Describe the changes in mineral components and texture of rocks due to changes in pressure and temperature (metamorphism)" (83%). This pattern implies that while contextualization works well for concrete, observable phenomena, it may require supplemental strategies when dealing with processes that occur deep within the Earth or over extended geological timescales.

The statistical analysis of pre-post differences yielded compelling evidence for the effectiveness of all three approaches. The paired-sample t-tests revealed statistically significant improvements ($p = 0.000$) for each method, with substantial effect sizes indicating meaningful educational impact rather than marginal gains. For PBL, student scores increased from a pretest mean of 20.83 to a posttest mean of 43.45; TBL showed growth from 27.31 to 45.20; and CBL demonstrated improvement from 21.80 to 42.93. These consistent and robust gains across all three conditions strongly support the implementation of active, student-centered approaches in Earth Science instruction. The findings align with contemporary educational research emphasizing the importance of engagement, authentic applications, and multimodal learning experiences in science education.

Despite these overall positive outcomes, the posttest data revealed persistent challenges in certain Earth Science competencies regardless of instructional approach. Under PBL conditions, students continued to struggle most with "Describe the changes in mineral components and texture of rocks due to changes in pressure and temperature (metamorphism)" and "Explain how the movement of plates leads to the formation of folds, faults, trenches, volcanoes, rift valleys, and mountain ranges." Similarly, TBL implementation still saw difficulties with plate movement explanations and ocean basin concepts, while CBL faced ongoing challenges with Earth's internal heat and magma formation processes. These consistent trouble spots across methodologies suggest inherent conceptual difficulties in these Earth Science topics that may require specialized instructional attention beyond general pedagogical approaches.

The identification of these persistent learning gaps has important implications for Earth Science education. Metamorphic processes, plate tectonics, and earth's internal systems appear to present unique cognitive challenges that demand targeted instructional strategies. Research in geoscience education suggests that these concepts require sophisticated spatial reasoning, understanding of immense timescales, and integration of multiple interacting systems—all of which are cognitively demanding for secondary-level students. The findings from this study reinforce the need for instructional materials and approaches that specifically address these challenging concepts through enhanced visualization tools, carefully designed learning progressions, and opportunities for students to actively work with and manipulate representations of these systems.

In response to these findings, the study proposes an integrated instructional framework that strategically combines elements of PBL, TBL, and CBL to address both general learning needs and specific conceptual challenges in Earth Science education. The proposed approach emphasizes a blended learning model where the strengths of each methodology are leveraged to create a comprehensive learning experience. For instance, technology-based simulations could be embedded within project-based investigations that are contextualized to local geological phenomena. This hybrid approach would allow students to benefit from the engagement and authenticity of PBL, the visualization and interaction capabilities of TBL, and the relevance and applicability of CBL—all within a cohesive instructional sequence.

The action plan specifically recommends using virtual labs and interactive simulations (TBL components) to help students visualize and experiment with abstract processes like metamorphism and plate tectonics. These digital tools could then be complemented by hands-on projects (PBL components) where students apply their understanding to analyze real-world geological features or solve authentic problems. Finally, contextualization (CBL components) would ground these activities in local examples and applications, helping students see the relevance of these concepts to their own environment and community. This integrative model aligns with current best practices in science education that emphasize multidimensional approaches to teaching complex scientific concepts.

The study's findings also highlight the importance of professional development for Earth Science educators to effectively implement these innovative teaching approaches. Teachers would need training not only in the technical aspects of using educational technology but also in designing meaningful projects and identifying appropriate local contexts for scientific concepts. Additionally, the development of high-quality curricular resources that support this integrated approach would be essential for widespread implementation. These resources might include ready-to-use project templates, curated digital simulations, and case studies linking earth science concepts to regional geological features.

Longitudinal aspects of Earth Science learning represent another important consideration emerging from this research. While the study demonstrated significant short-term gains in conceptual understanding, the retention and transfer of these earth science concepts over time would be an important area for future investigation. Additionally, research could explore how these approaches affect not only content knowledge but also students' scientific reasoning skills, interest in geosciences, and ability to apply earth science concepts to new situations or problems. The development of scientific literacy and earth science competency has become increasingly important in our era of climate change and environmental challenges, making these educational outcomes particularly significant.

The study also invites reflection on assessment practices in Earth Science education. The consistent identification of certain competencies as challenging across multiple approaches suggests that these topics may require alternative assessment strategies to accurately gauge student understanding. Traditional testing methods may not fully capture students' evolving conceptions of complex earth systems, pointing to the potential value of performance-based assessments, concept mapping, or other alternative evaluation approaches that can better reveal nuanced understanding of geological processes.

Implementation considerations for schools looking to adopt these approaches must account for varying levels of technological infrastructure, teacher preparedness, and curricular flexibility. While the results strongly support the effectiveness of these innovative methods, their successful implementation would require careful planning and support. Schools might consider phased implementation, starting with pilot programs that allow for refinement before school-wide adoption. The study's findings provide compelling evidence to support such investments in pedagogical innovation, particularly in the crucial area of Earth Science education.

The broader implications of this research extend to science education policy and curriculum development. The demonstrated effectiveness of these active learning approaches suggests that they should be more prominently incorporated into Earth Science standards and instructional guidelines. Curriculum developers might use these findings to inform the design of instructional materials that better address known conceptual challenges in earth science learning. Additionally, teacher education programs could emphasize these pedagogical strategies to better prepare new educators for the challenges of teaching Earth Science effectively.

In conclusion, this study makes significant contributions to our understanding of effective Earth Science instruction at the secondary level. The robust evidence for the effectiveness of PBL, TBL, and CBL approaches provides educators with research-backed alternatives to traditional lecture-based methods. At the same time, the identification of persistent conceptual challenges offers important guidance for focusing instructional improvement efforts. The proposed integrated approach represents a promising path forward for enhancing Earth Science education, with potential benefits for student learning, engagement, and the development of scientific literacy needed to address pressing geoscience-related challenges in our society. Future research building on these findings could further refine our understanding of how to best support Earth Science learning and could explore the transferability of these approaches to other science disciplines or educational contexts.

CONCLUSION

The study's findings present compelling evidence about the effectiveness of innovative teaching approaches in Earth Science education, while simultaneously revealing persistent challenges that require targeted instructional solutions. The investigation into Project-Based Learning (PBL), Technology-Based Learning (TBL), and Contextualized-Based Learning (CBL) approaches with Grade 11 STEM students at Cabadbaran City National High School yielded significant insights that contribute to both theoretical understanding and practical applications in science pedagogy. The pretest results established a crucial baseline, demonstrating that students entered the study with partial mastery of Earth Science concepts, scoring at a "Nearly Proficient" level overall (60% MPS), but with notable deficiencies in specific competencies related to geological processes and earth systems. The pattern of pretest performance revealed consistent difficulties with abstract concepts involving large-scale earth processes—particularly those requiring visualization of phenomena that are not directly observable in students' everyday experiences. The lowest pretest scores in competencies like "Describe the structure and evolution of ocean basins" (44%) and "Describe how rocks behave under different types of stress" (58%) highlighted fundamental gaps in understanding dynamic earth systems that traditional instruction had failed to adequately address. These initial findings align with broader science education research that has identified earth science and geological processes as particularly challenging areas for secondary students, often due to the abstract nature of the content, the immense timescales involved, and the complex systems thinking required.

The post-intervention results demonstrated remarkable improvements across all three teaching approaches, validating their effectiveness as alternatives to conventional instructional methods. The statistically significant gains ($p = 0.000$) in posttest scores—with TBL achieving the highest overall mean percentage score (93%), followed by PBL (90%) and CBL (89%)—provide robust empirical support for adopting these active learning strategies in Earth Science classrooms. The superior performance under TBL conditions suggests that technology integration offers unique advantages for teaching Earth Science concepts, likely due to its capacity to visualize abstract processes, provide interactive simulations, and offer personalized learning pathways. Digital tools appear particularly effective in helping students grasp concepts that are otherwise difficult to observe directly, such as plate tectonics or metamorphic processes. The strong performance across all three approaches nevertheless indicates that the active, student-centered nature of PBL, TBL, and CBL—rather than any single approach in isolation—may be the key factor driving improved learning outcomes. This interpretation aligns with contemporary learning theories emphasizing the importance of engagement, authentic application, and multimodal experiences in meaningful science learning.

Despite these overall positive outcomes, the study revealed persistent conceptual challenges that warrant careful consideration. Analysis of posttest results identified certain competencies—particularly those related to metamorphism, magma formation, and plate tectonics—that remained relatively difficult for students across all three instructional approaches. This pattern suggests that while PBL, TBL, and CBL are effective at improving general Earth Science understanding, they may need targeted enhancements or combined implementation to fully address the most cognitively demanding concepts. The recurring difficulties with these topics likely stem from their inherent complexity, requiring students to integrate multiple systems, understand processes occurring across vast timescales, and visualize phenomena at scales ranging from microscopic mineral changes to continental movements. These findings echo challenges identified in international Earth Science education research, where similar concepts have been recognized as persistent trouble spots requiring specialized instructional attention.

The study's results have important implications for curriculum design and instructional practice in Earth Science education. The demonstrated effectiveness of all three approaches suggests that schools should move beyond traditional lecture-based methods and incorporate more active, student-centered pedagogies. However, the varying performance across different competencies indicates that a one-size-fits-all approach may be insufficient. Instead, educators might adopt a strategic, differentiated implementation where specific approaches are matched to particular learning objectives based on their relative strengths. For instance, TBL's superior performance in visualizing abstract processes suggests it should be prioritized for teaching topics like plate tectonics or rock deformation, while CBL's real-world connections might be more valuable for surface processes or local geological applications. PBL's collaborative, investigative nature could be particularly effective for integrating multiple concepts through extended projects. This nuanced application requires careful curriculum analysis and teacher professional development to ensure appropriate matching of pedagogical approaches to learning objectives.

The study also highlights the critical role of technological integration in modern Earth Science education. TBL's strong performance underscores how digital tools can transform the teaching of traditionally challenging concepts by making the invisible visible and the abstract concrete. Virtual simulations, interactive 3D models, and data visualization tools appear to provide cognitive scaffolding that helps students overcome the spatial and temporal challenges inherent in geological concepts. This finding is particularly relevant in today's educational landscape, where digital literacy and technology integration are increasingly recognized as essential components of STEM education. Schools investing in Earth Science programs should prioritize acquiring appropriate technological tools and providing teachers with the training needed to use them effectively. However, the study also cautions against over-reliance on technology alone, as even TBL had areas of relative weakness that might be addressed by combining it with other approaches.

The social and collaborative aspects of PBL emerged as another significant finding with implications for classroom practice. While PBL's overall effectiveness was slightly below TBL, its emphasis on collaborative investigation, problem-solving, and authentic applications appears to contribute uniquely to student learning. The social construction of knowledge through group projects and discussions likely helps students articulate and refine their understanding of Earth Science concepts. This aligns with sociocultural learning theories emphasizing the importance of discourse and shared meaning-making in science education. Teachers implementing PBL should focus on creating well-structured group activities with clear roles, meaningful tasks, and opportunities for reflection to maximize these benefits.

Contextualized learning showed particular promise for connecting abstract Earth Science concepts to students' lived experiences and local environments. While CBL had the lowest overall posttest scores among the three approaches, its emphasis on real-world relevance appeared to engage students and help ground theoretical knowledge in practical applications. The study suggests that contextualization may be especially valuable for making Earth Science personally meaningful and culturally relevant to students—a factor known to enhance motivation and long-term retention. Educators should seek opportunities to connect curriculum content to local geological features, environmental issues, or community concerns to capitalize on these benefits. However, the findings also indicate that contextualization alone may be insufficient for teaching highly abstract concepts, suggesting the need to combine CBL with other approaches when addressing topics like earth's internal processes or metamorphism.

The identification of persistent learning difficulties across all three approaches points to the need for targeted instructional innovations in specific Earth Science content areas. Concepts related to metamorphism, plate tectonics, and earth's internal processes consistently emerged as challenging despite varied teaching methods. This pattern suggests these topics may require specialized instructional strategies beyond general active learning approaches. Research-based interventions might include enhanced visualization tools, carefully sequenced learning progressions, or conceptual change strategies specifically designed for these troublesome concepts. Teacher education programs should emphasize these challenging areas and provide educators with a repertoire of specialized techniques for addressing them.

The study's findings also contribute to ongoing discussions about assessment in Earth Science education. The consistent identification of certain competencies as challenging across multiple approaches suggests that traditional assessment methods may not fully capture students' understanding of complex earth systems. Alternative assessment strategies—such as concept mapping, model-based reasoning tasks, or simulation-based assessments—might provide more nuanced insights into student thinking about geological processes. The development of such assessments could better support teachers in identifying and addressing specific conceptual difficulties.

Professional development emerges as a critical factor in light of these findings. Successful implementation of PBL, TBL, and CBL approaches requires teachers to develop new pedagogical skills, technological competencies, and content-specific instructional strategies. Effective professional development programs should not only introduce these approaches but also provide ongoing support as teachers adapt them to their specific classroom contexts. Collaborative professional learning communities could be particularly valuable for sharing best practices and troubleshooting implementation challenges.

The study also has implications for educational policy and resource allocation. The demonstrated effectiveness of these approaches suggests that education systems should prioritize funding for teacher training, technological infrastructure, and the development of high-quality instructional materials that support PBL, TBL, and CBL in Earth Science. Curriculum frameworks might need revision to allow for the more time-intensive nature of these pedagogies compared to traditional instruction. Such systemic support would help ensure that these research-based approaches can be implemented effectively at scale.

Longitudinal research is needed to examine whether the observed learning gains persist over time and how they affect students' subsequent engagement with Earth Science. Additionally, studies comparing different combinations or sequences of these approaches could provide guidance on optimal implementation strategies. Research exploring how these methods affect diverse student populations would help ensure equitable access to effective Earth Science instruction.

The study's proposed Daily Lesson Log represents a practical tool for implementing these research findings in classroom settings. By incorporating elements of PBL, TBL, and CBL within a structured framework, the DLL aims to make these approaches accessible to teachers while maintaining flexibility for adaptation to local contexts. The DLL's emphasis on student-centered activities, real-world applications, and technological integration reflects the study's key findings about effective Earth Science instruction. This resource could significantly lower the implementation barrier for teachers seeking to adopt these approaches.

In conclusion, this study makes significant contributions to our understanding of effective Earth Science instruction at the secondary level. The robust evidence for PBL, TBL, and CBL provides educators with research-backed alternatives to traditional methods, while the identification of persistent conceptual challenges offers crucial guidance for targeted instructional improvement. The findings collectively suggest that transforming Earth Science education requires both adopting these innovative pedagogies and addressing specific learning difficulties through tailored strategies. The integrated approach proposed by the study—combining the strengths of multiple methods while addressing their limitations—represents a promising path forward for enhancing Earth Science teaching and learning. As society faces increasing geological and environmental challenges, developing students' understanding of Earth systems becomes ever more critical. This study provides both evidence and direction for educational efforts to meet this vital need, ultimately contributing to the development of scientifically literate citizens capable of engaging with complex Earth-related issues. The journey toward effective Earth Science education continues, but this research illuminates productive pathways worth exploring further through both classroom practice and ongoing investigation.

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