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Exploring the Transferability of STEM PBL Instructional Principles from Higher Education to K-12 Classrooms

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Abstract: The first objective of this study was to explore which principles of STEM PBL instruction pre-service teachers found most beneficial in enhancing their understanding of mathematics- and science-related concepts. The second objective was to identify the instructional practices from STEM PBL that pre-service teachers intended to incorporate into their future teaching practices. We conducted a descriptive qualitative study, analyzing data from interviews (n = 8), reflections, and classroom artifacts (n_{total} = 43). The findings revealed 12 distinct themes: six associated with the first objective and six linked to the second objective. Two themes—communication and real-world relevance—emerged as common across both objectives. The significance of this study lies not only in identifying key principles of STEM PBL but also in highlighting the need to emphasize these principles in various instructional methods, enhancing the transferability of innovative practices to future teachers' mathematics classrooms.

Keywords: STEM PBL; PBL principles; pre-service teachers; instructional practices

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1. Introduction

The evolving demands of the 21st-century workforce require innovative teaching strategies, particularly in Science, Technology, Engineering, and Mathematics (STEM) education, to foster essential skills like creativity, critical thinking, problem solving, and collaboration. Project-based learning (PBL) has emerged as a leading approach, allowing students to engage with real-world challenges while developing these skills (Capraro & Slough, 2013; Navy & Kaya, 2020). PBL deepens students' understanding of STEM concepts while enhancing engagement and STEM interest (Beier et al., 2019; Lou et al., 2017). However, its success depends largely on teachers' readiness and confidence in implementing it effectively (Capraro et al., 2016; Darling-Hammond, 2000), making pre-service teacher preparation essential.

Despite the proven benefits of PBL, a significant gap remains in equipping pre-service teachers with the practical skills to implement it in classroom settings (Brears et al., 2011; Dean et al., 2023). Many teacher education programs emphasize the theory behind PBL but provide insufficient hands-on experience, leaving pre-service teachers unprepared to apply these principles in practice (Bicer & Lee, 2019; Han et al., 2015). This gap underscores the need for programs to focus on experiential learning and reflective practice, approaches that build the competence and confidence necessary for successful PBL implementation (Brears et al., 2011; Martinez, 2022).

Research shows that pre-service teachers benefit most from engaging with PBL as learners themselves. By experiencing learner-centered practices firsthand, they can internalize PBL principles and become better prepared to create dynamic, student-centered

classrooms (Darling-Hammond & McLaughlin, 2011). Scaffolded, modeled, and collaborative PBL experiences improve pre-service teachers' ability and confidence to implement PBL in the classroom, enabling them to better engage students with both content and pedagogy (Bhattacharyya & Bhattacharya, 2009; Saye & Brush, 2004; Wynn & Okie, 2017). Although research on PBL in teacher education is still emerging, studies consistently demonstrate its effectiveness in enhancing pre-service teachers' critical thinking, problem-solving, and pedagogical skills through collaborative inquiry, authenticity with real-life challenges, and reflective practices (Brears et al., 2011; Erdogan & Senemoglu, 2017; Martinez, 2022; Pitot et al., 2024; Wynn & Okie, 2017).

Nonetheless, significant challenges remain in preparing pre-service teachers to implement PBL effectively. Many programs still limit PBL exposure to single disciplines, neglecting its potential for interdisciplinary integration (Brears et al., 2011). Additionally, pre-service teachers often lack opportunities to develop a clear mental model of effective PBL principles, which is crucial in transferring them into their future practices (Alrajeh, 2021; Erdogan & Senemoglu, 2017). This study addresses these gaps by examining how pre-service teachers engage with PBL in a 15-week interdisciplinary STEM methods course. Focusing on their reflections, interviews, and classroom artifacts, it aims to explore the PBL principles that pre-service teachers find most valuable and their plans to implement these principles in their future classrooms.

1.1. Core Principles of STEM Project-Based Learning (PBL)

STEM PBL is an instructional approach designed to engage students in meaningful, real-world problem-solving tasks by integrating multiple disciplines and encouraging students to solve complex problems by applying knowledge across subjects. This *hands-on approach* mimics how STEM professionals work in real life to cultivate 21st-century skills such as critical thinking, collaboration, and self-directed learning (Capraro & Slough, 2013; Lou et al., 2017; Navy & Kaya, 2020). The open-ended nature of PBL tasks challenges students to think beyond memorization and standardized responses and encourages them to engage in inquiry-driven exploration, peer collaboration, and interdisciplinary learning (Lattimer & Riordan, 2011). At the heart of PBL, there are several key principles that are essential in STEM education, where solving complex and real-world problems requires critical thinking, collaboration, and interdisciplinary knowledge.

One key principle of PBL is its focus on *ill-defined tasks* paired with *well-defined outcomes*. Students are presented with open-ended problems that do not have a single correct solution, requiring them to engage in problem solving, explore multiple pathways, and reflect on uncertainties, much like in real-world STEM professions (Bicer, 2021; Capraro & Slough, 2013). Despite the ambiguity in approaching the problem, the well-defined outcomes provide clear goals and standards to guide students. This balance between task flexibility and outcome clarity fosters *creative problem solving and innovation and critical thinking*, ensuring that students develop solutions while meeting essential learning objectives and standards (Bicer et al., 2021; Capraro & Slough, 2013; Lee et al., 2019).

Another critical principle is the focus on *authentic problems* and *real-world connections*. By centering projects around real-world challenges, PBL ensures that learning is engaging and relevant to students' lives (Chang et al., 2024). This real-world relevance encourages students to approach problems through extended inquiry, often in collaboration with their peers, and to draw on *interdisciplinary knowledge* (Lattimer & Riordan, 2011; Le et al., 2023). When students see the practical applications of STEM concepts in everyday situations, their motivation and interest in STEM careers naturally increase as they understand how their learning can make a tangible impact (Beier et al., 2019; Lou et al., 2017).

Inquiry-based learning, which emphasizes students actively asking questions and seeking solutions through exploration and investigation, aligns with the principles of open-ended problem solving and real-world inquiry. It fosters critical thinking and deep engagement with content as students develop their own inquiries and explore various paths to solutions (Singha & Singha, 2024). This principle promotes creativity as students move from passive recipients of information to active participants, driving their learning process and discovery of STEM concepts (Kolodner et al., 2003).

In addition to solving real-world problems through interdisciplinary knowledge, *collaborative learning and teamwork* are integral to PBL. Working in groups, students share ideas, solve problems collectively, and benefit from diverse perspectives (Kokotsaki et al., 2016). This collaboration mimics how STEM professionals work and enhances students' communication and negotiation skills and interpersonal competence, preparing them for the team-oriented nature of modern workplaces (Crespí et al., 2022; Fang, 2012; Hart, 2019). *Student autonomy and ownership* complement this collaborative approach by giving learners control over their learning process. Students are empowered to decide how they approach their tasks, solve problems, and manage their processes, further cultivating their self-reliance and personal responsibility (Hall & Miro, 2016; Kokotsaki et al., 2016; Yuliani & Lengkanawati, 2017). Moreover, this autonomy allows students to explore topics that interest them, leading to greater engagement and intrinsic motivation. By balancing teamwork with individual responsibility, PBL both strengthens students' ability to collaborate and enhances their independence—both of which are crucial for success in future STEM careers (Beier et al., 2019; LaForce et al., 2017).

With the increasing autonomy of students, students also work collaboratively with teachers to establish clear and achievable goals and to make decisions regarding the pace, sequencing, and content of their learning (Yuliani & Lengkanawati, 2017). This shift in responsibility from the teacher to the students creates a culture that expects learners to be accountable for their learning outcomes, with teachers providing guidance and support as needed (Kokotsaki et al., 2016). So, in PBL, the *role of the teacher* shifts from that of a lecturer to a *facilitator or coach*—instead of delivering content through direct instruction, teachers provide guidance and scaffolding, offering support when needed and gradually withdrawing as students gain confidence (Kokotsaki et al., 2016; Yuliani & Lengkanawati, 2017). This approach encourages students to develop problem-solving skills and become more self-directed, fostering their ability to navigate complex challenges independently while benefiting from structured support (Hall & Miro, 2016; Kokotsaki et al., 2016; Yuliani & Lengkanawati, 2017).

Technology integration further enhances STEM PBL by enabling students to visualize abstract concepts and apply them to real-world contexts. Tools such as dynamic mathematics software, augmented reality, and 3D printing help to make complex ideas more accessible through simulations and multiple representations (Haas et al., 2023). Additionally, technology integration like implementing virtual reality in mathematics and science classrooms creates immersive experiences that bring theoretical concepts to life (Oluseye et al., 2020). Web-based platforms like Weave facilitate collaborative data exploration, allowing students to work together in interactive, inquiry-based environments (Baumann et al., 2011). By embedding technology into PBL, educators can deepen student engagement in problem solving and engineering design processes, while fostering a more comprehensive understanding of STEM concepts (Yang & Baldwin, 2020).

However, some students may struggle to relate their PBL experiences directly to professional STEM practices, highlighting the importance of *structured reflection* that bridges the gap between academic learning and real-world application (Luo et al., 2024). By providing intentional opportunities for reflection that connect students' classroom activities to

real-world STEM practices, teachers can support students in internalizing their learning experiences and connecting theory and practice while improving their metacognitive skills (Lynch et al., 2012; Maor et al., 2023). *Performance-based assessment* and the *integration of self-assessment and peer evaluation* further enrich the PBL experience by offering meaningful, formative feedback that promotes accountability and growth (Lynch et al., 2012; Maor et al., 2023). Unlike traditional assessments, performance-based assessments evaluate students' ability to apply knowledge in practical, real-world contexts—whether through project milestones, presentations, or design prototypes (Feldon et al., 2010). This ongoing assessment process encourages continuous improvement as students receive feedback throughout the project lifecycle, allowing them to refine their work and approaches iteratively. Self-assessment plays a critical role by prompting students to take ownership of their learning journey, reflect on their progress, and critically evaluate their strengths and areas for growth (Kokotsaki et al., 2016; Wang et al., 2021). Additionally, peer evaluation introduces a collaborative layer, where students offer constructive feedback to one another, enhancing both their communication and teamwork skills (Chang et al., 2024). Together, these assessment methods both measure student performance and foster a culture of continuous improvement, critical thinking, and self-awareness. However, realizing the full potential of PBL in STEM education not only depends on the effective design of these principles but also on their successful implementation (Grossman et al., 2021). Thus, instructional practices are equally important in ensuring that these principles translate into meaningful learning experiences for students.

1.2. Preparing Pre-Service Teachers for Effective STEM PBL Instruction

While the principles of STEM PBL, such as real-world relevance, collaboration, and inquiry-based learning, provide students with valuable opportunities to develop 21st-century skills, their success in the classroom is largely dependent on the teacher's ability to facilitate these practices effectively (Capraro & Slough, 2013; Grossman et al., 2021). This makes the preparation of pre-service teachers critical, as they must be equipped not only with theoretical knowledge but also with the practical skills needed to implement innovative instructional approaches like PBL (Brears et al., 2011; Han et al., 2015; Martinez, 2022; Saye & Brush, 2004). Increasingly, teacher education programs focus on developing pre-service teachers' skills and readiness to implement STEM PBL in their future classrooms, recognizing the need for a balance between theory and hands-on practice.

One effective strategy for the preparation of pre-service teachers is through interdisciplinary collaboration. Teacher preparation programs often encourage pre-service teachers from different STEM disciplines to work together to design integrated STEM projects. This strategy challenges them to draw connections between various STEM subjects and apply these concepts to real-world problems (Adams et al., 2014). Such collaboration not only enhances their understanding of STEM integration but also helps them to develop communication skills across different fields, which are crucial in fostering interdisciplinary learning in their future classrooms (An, 2020; Chai et al., 2020).

Another critical aspect of preparation is providing pre-service teachers with authentic design experiences. Engaging them in hands-on activities where they actively design and develop STEM PBL lessons allows them to understand how to translate theoretical knowledge into classroom applications. For example, creating materials that integrate multiple STEM fields around a central design challenge mirrors the real-world challenges that they will encounter in their careers (Chai et al., 2020; Martinez, 2022). These experiences build their confidence in creating cohesive projects that incorporate multiple STEM disciplines while addressing real-world problems.

Furthermore, fostering a student-centered approach in pre-service teachers is essential for PBL instruction. Programs are increasingly emphasizing the shift from traditional teacher-directed instruction to student-led inquiry, encouraging pre-service teachers to design lessons that promote active problem solving and exploration by students (Brears et al., 2011; Wynn & Okie, 2017). By placing the focus on student inquiry and relevance, pre-service teachers learn to facilitate environments where students take ownership of their learning process, promoting deeper engagement and critical thinking (Domenici, 2022; Saye & Brush, 2004).

Technology integration also plays a key role in preparing pre-service teachers for STEM PBL instruction. Teacher preparation programs must ensure that pre-service teachers are proficient in using technology both as a learning tool for students and as a means of designing and delivering STEM PBL activities (Akgun, 2013). Technologies such as 3D printing, coding environments, and digital design tools are invaluable resources in STEM education, and pre-service teachers need hands-on experience with these tools to effectively integrate them into their future classrooms (Chai et al., 2020).

Reflective practice is another vital component in preparing pre-service teachers for effective PBL instruction. Through reflection, pre-service teachers can critically assess their own experiences in designing and implementing PBL activities. This self-assessment helps to refine their instructional strategies and better prepares them to handle the complexities of facilitating open-ended, interdisciplinary learning in real classroom environments (Domenici, 2022; Brears et al., 2011). Reflective practice becomes even more important when considering the challenges that pre-service teachers face in traditional school environments, where factors like time constraints and curriculum standards often limit the scope of interdisciplinary integration (Erdogan & Senemoglu, 2017).

Despite the progress in teacher preparation, challenges remain in fully equipping pre-service teachers with the skills needed to implement PBL effectively. Many programs still provide limited opportunities for interdisciplinary experiences, leaving pre-service teachers uncertain about how to facilitate learning across multiple STEM subjects (Brears et al., 2011). Additionally, the lack of hands-on experiences where pre-service teachers can practice managing open-ended tasks and facilitating student-led inquiry can hinder their ability to confidently implement these practices in their future classrooms (Han et al., 2015). Addressing these gaps requires teacher preparation programs to offer more opportunities for experiential learning, where pre-service teachers can engage in real or simulated PBL experiences that mirror the complexities of classroom instruction (Darling-Hammond & McLaughlin, 2011). This study addresses these needs by examining how pre-service teachers engage with STEM PBL principles in a 15-week interdisciplinary STEM methods course. Throughout the course, pre-service teachers participated in project-based learning activities designed to mirror the experiences that their students would later engage in. The research questions guiding this study were as follows:

- How do pre-service teachers perceive the principles of project-based learning (PBL) as supporting their learning in an interdisciplinary STEM methods class?
- Which principles of PBL do pre-service teachers intend to implement in their future instructional practices?

2. Method

A descriptive qualitative study—specifically a single-site, multiple-subject case study (Gustafsson, 2017) was conducted to explore the principles of STEM PBL instruction that contributed to the development of pre-service teachers' science and mathematics learning, as well as the principles that they planned to implement in their future teaching. The case study approach was chosen because it allowed for an in-depth exploration of the specific

instructional context and the diverse experiences of multiple pre-service teachers within a single site. This design enabled the researchers to capture the nuanced interplay between the instructional principles of STEM PBL and their impacts on individual participants. Semi-structured face-to-face interviews, along with classroom reflections and classroom artifacts, were used to collect data, ensuring a comprehensive understanding of the participants' perspectives and practices.

2.1. Participants and Setting

The participants were recruited from the teacher education program at a university in the northwestern United States. They were pre-service teachers who would be certified to teach in grades K-6. They enrolled in their required mathematics and science methods courses during the implementation of the STEM PBL intervention. The intervention took place in two sessions, involving 43 pre-service teachers: 35 females and 8 males. Purposive sampling (Korstjens & Moser, 2018) was used to select participants, aiming for diversity in terms of gender, race, and prior achievement in STEM-related courses. However, the majority of the pre-service teachers were White, female, and traditional college-aged students. Recruitment was conducted by advertising the two specific sessions before the semester started. Students were informed about the session design, and volunteer pre-service teachers interested in participating in the STEM PBL-focused mathematics and science methods course were selected on a first-come, first-served basis. Of the 47 participants initially contacted, 43 consented to participate.

Prior to this intervention, the course was structured so that the PSTs spent half of the semester in the mathematics methods course and the other half in the science methods course. With the STEM PBL intervention, our aim was to integrate science and mathematics throughout the semester, providing the PSTs not only with an interdisciplinary approach to STEM concepts to enhance their understanding of mathematics and science but also with opportunities to develop pedagogical knowledge of innovative instructional practices—specifically the principles of STEM PBL. The semester lasted 15 weeks, and the PSTs received 5 h of STEM PBL instruction. This included 13 weeks of engagement with instructor-designed projects and two weeks during which the PSTs, in groups, created and taught their own STEM PBL lessons as part of their final assignment.

The instructor-designed projects included, but were not limited to, parachute design, balloon cars, catapults, trebuchets, bridge building, paper engineering, cryptography, 3D printing and Tinkercad design, city building, drone design, and speaker design. The instructor not only provided the pre-service teachers with opportunities to construct their projects while learning mathematics, science, technology, and engineering concepts, but also explicitly supported the theoretical features of STEM PBL. These features were introduced through hands-on practice and reflective discussions. For example, after the groups conducted their first trial of their parachute designs, they were given the opportunity to analyze the results, make modifications to their designs, and test them again. This iterative process was then explicitly connected to an important dimension of engineering design principles—emphasizing the importance of trial and error, redesign, and optimization in STEM PBL lessons. Similarly, the PSTs observed and experienced other key features of STEM PBL, such as fostering collaboration, encouraging problem solving, and integrating interdisciplinary approaches. These features were not only explained by the instructor but were also experienced firsthand by the PSTs during the activities, providing them with a practical and immersive understanding of how to implement these principles effectively in their own teaching. The projects created and taught by the PST groups were similar in nature, with one example being a wind tower design lesson. All STEM PBL lessons

were designed to demonstrate how pre-service teachers could merge science and math instruction while incorporating technology and engineering design principles.

2.2. Data Collection and Data Analysis

The principal researcher drafted the outline for the semi-structured interview by reviewing the relevant literature on STEM PBL practices and discussing it with the research team. The interview included the following questions: (a) Which instructional practices of STEM PBL were helpful for you in understanding mathematics and science concepts? (b) Which instructional practices of STEM PBL enabled you to deepen your existing understanding of scientific and mathematical ideas? (c) Do you plan to implement any principles of STEM PBL instruction in your future classes? If yes, what practices do you think you will implement? If no, why? Additional questions were asked based on the participants' responses. For clarification, the instructor of the course was involved in the research, both as a facilitator of the STEM PBL activities and as a contributor to the course design. The course was intentionally designed to align with the objectives of the research project, aiming to integrate STEM PBL principles into pre-service teachers' learning experiences.

The interviews were conducted in the week following the end of the semester, lasting between 30 and 40 min. During the semester, the participants also provided reflections after each class session. These reflections focused on what aspects of the STEM PBL activities were most helpful for their understanding of math and science concepts and which principles they wished to implement in their future classrooms. In addition, classroom artifacts—such as end products, notes, and problem solutions—were collected. The data from these reflections, classroom artifacts, and interviews were triangulated for analysis to ensure a comprehensive understanding of the participants' experiences. The interviews were designed to be open-ended, encouraging the pre-service teachers (PSTs) to share their authentic experiences and perspectives. To minimize potential bias, the questions did not directly lead the participants to predetermined answers but instead encouraged them to reflect on their own learning and teaching practices. For the analysis, two authors independently transcribed two interviews and collaboratively discussed the meanings of the codes using the NVivo software and thematic analysis (Kiger & Varpio, 2020). They reached a consensus on a coding framework and applied it independently to the remaining interviews. When no new codes emerged, it was determined that data saturation had been achieved (Korstjens & Moser, 2018). While the PSTs were introduced to the foundational features of STEM PBL as part of their preparation, this was intended to provide a framework for engagement and not to prescribe their responses. The reflections and interviews were focused on capturing their unique and personal insights, shaped by their experiences rather than prior instruction. By triangulating data from multiple sources and ensuring robust coding practices, we aimed to ensure the validity and depth of the findings while addressing potential concerns about bias.

3. Results

Our data revealed six themes for each research question. For the first research question, the six themes highlighting the principles of STEM PBL instruction that were helpful for pre-service teachers (PSTs) were real-world application, critical thinking and problem solving, collaborative learning, interdisciplinary learning, hands-on and experiential learning, and creativity and innovation. For the second research question, the six themes illustrating the principles of STEM PBL instruction that the PSTs planned to implement in their future teaching were student autonomy, inquiry-based learning, open-ended tasks, collaboration and teamwork, the integration of technology, and real-world relevance. Two themes—real-world application and collaborative learning—were common to both research

questions. The following themes emerged in response to the first research question: "Which characteristics of STEM PBL help PSTs to develop their understanding of mathematics and science concepts?" The project was intentionally designed based on the specific features and benefits of STEM project-based learning (PBL) as outlined in the literature. The pre-service teachers (PSTs) were introduced to these features during the preparation phase of the project to ensure a clear understanding of PBL's potential purposes and benefits. However, this introduction was not intended to prescribe or limit their responses but rather to provide them with a foundational understanding of STEM PBL. During their participation, the PSTs were encouraged to critically reflect on their experiences and to articulate the elements of STEM PBL that they personally found significant or impactful. While their responses naturally overlapped with the literature due to the alignment of the project design with established PBL principles, the goal was to allow their authentic experiences and interpretations to surface. The themes that they identified were not merely restatements of what they had been taught but rather reflections of how these elements manifested and resonated in their practice. This alignment supports the reliability of the findings while validating the theoretical framework of STEM PBL.

3.1. Real-World Application

The PSTs found that STEM PBL effectively connected what they learned in mathematics and science to real-world situations, making these subjects more relevant and meaningful. Through projects rooted in real-world challenges, they could see the practical application of their academic knowledge. As PST 1 stated, "Working on real-world problems made the mathematics and science we learned feel more useful. It wasn't just theory anymore; we could see how it applied to things we care about". A more specific example was provided by PST 7, who highlighted the connection between mathematics and science through real-world applications: "I liked how we used mathematics to solve problems that could actually happen in life, like calculating how much energy a solar panel could generate. It made everything more practical". It seems that the PSTs believed that connecting mathematics and science to real-world applications increased their motivation to solve complex STEM-related problems. For instance, PST 5 shared, "Science became more interesting when I saw how we could use what we learned to improve real situations, like water filtration systems". These and similar statements emphasized how the PSTs valued the real-life applications of the projects, which enabled them to meaningfully engage with and learn about mathematics and science.

3.2. Critical Thinking and Problem Solving

The second theme that emerged from the data was critical thinking and problem solving. Many PSTs noted that STEM PBL encouraged them to think critically while solving complex, challenging problems that required them to analyze, synthesize, and evaluate information to develop solutions. For example, PST 3 shared, "The projects made me think more deeply about how to apply different math formulas and concepts. It wasn't just about memorizing. I had to figure out when and how to use what I learned". PST 2 highlighted how the interdisciplinary nature of STEM PBL pushed her to think critically: "STEM PBL really challenged me to solve problems in ways that weren't straightforward. I had to combine science and math to come up with a solution, which made me a better thinker". Many participants appreciated that the ill-defined nature of STEM PBL tasks led them to solve problems by thinking critically in their own way. As PST 8 noted, "I think it helped me develop stronger problem-solving skills because the challenges weren't always clear-cut, and we had to come up with solutions on our own". While critical thinking and problem solving were common themes across many responses, the PSTs specifically

mentioned practices such as ill-defined tasks, multiple-solution tasks, interdisciplinary approaches, and cognitively challenging activities. These principles of STEM PBL fostered their ability to think critically and solve complex, real-world problems. In summary, the critical thinking and problem-solving skills developed through STEM PBL were deeply influenced by the complexity and openness of the tasks, along with the integration of multiple disciplines. This approach encouraged the PSTs to engage with the content more thoughtfully and independently, better preparing them for the challenges that they may face in future instruction.

3.3. Collaborative Learning

Collaborative learning or teamwork emerged as another key theme from the data, with the PSTs recognizing collaboration as an essential principle of STEM PBL. Many felt that working in groups allowed them to share ideas, learn from their peers, and solve problems more effectively. This collaborative aspect mirrored real-world STEM environments, as several PSTs pointed out. For instance, PST 6 shared, "Working with my classmates on the projects helped me see different ways to approach a problem. Someone else would think of a math solution I hadn't thought of, and we learned from each other". The value of discovering different approaches through group work was echoed by PST 5 and others, with PST 5 stating, "In our group, we all contributed different ideas from science and math, and it helped us figure out better ways to solve problems together". Many participants also highlighted how collaboration made complex, cognitively challenging problems in science and math more manageable. As PST 7 explained, "It was great working in a team because we bounced ideas off each other. I realized that collaboration made understanding harder concepts in both math and science easier". While the PSTs mentioned several aspects of collaboration in relation to STEM PBL, they predominantly emphasized two key benefits: seeing multiple solutions to problems and making difficult tasks more achievable through teamwork. This collaborative dynamic not only enhanced their learning but also mirrored the kind of teamwork that they would encounter in real-world STEM professions.

3.4. Interdisciplinary Learning

The PSTs appreciated how STEM PBL integrated multiple subjects, such as math, science, and often technology and engineering. This interdisciplinary approach helped them to understand the connections between different fields and how knowledge in one area can support learning in another. For instance, PST 1 shared, "What I liked most was seeing how math and science work together. When we built the model, we needed both the math to measure and calculate, and the science to understand how it would function". They particularly valued the opportunity to observe that math and science are not isolated from each other. As PST 5 noted, "STEM PBL showed me that math and science aren't separate subjects. They actually go hand-in-hand, especially when solving real-life problems". Many PSTs emphasized how this interdisciplinary approach helped them to grasp scientific or mathematical ideas that they might not have fully understood without seeing the connections between the subjects. For example, PST 4 said, "I realized through the projects how closely math and science are connected. We used math to make sense of difficult science concepts, and it helped us interpret scientific data and predictions". From these reflections, it is clear that the PSTs valued the interdisciplinary nature of STEM PBL primarily because it helped them to recognize the relationship between mathematics and science. Additionally, it allowed them to make challenging concepts in one subject more accessible by leveraging their strengths, prior knowledge, and experiences from another field.

3.5. Hands-On and Experiential Learning

Most PSTs emphasized the value of hands-on activities in STEM PBL. Engaging directly with the materials and experiments allowed them to apply theoretical and abstract knowledge in a practical setting, which deepened their understanding of math and science concepts. As PST 2 explained, "Doing experiments made the math and science concrete. When we tried things ourselves, it was easier to understand the concepts behind them". PST 4 echoed the importance of hands-on learning in making abstract concepts more tangible, saying, "I liked that we actually built something. It helped me understand the math behind it because I could see the results physically, not just on paper". Similarly, PST 1 shared, "The hands-on approach made the science concepts click for me. I learn better when I'm actually doing something, not just listening". These and other similar reflections from the PSTs show that hands-on learning and experimentation were particularly valuable. They found that these activities made abstract and complex concepts more tangible and manageable, while also actively involving them in their own learning processes.

3.6. Creativity and Innovation

STEM PBL fostered creativity by providing the PSTs with the freedom to explore and innovate. They valued the opportunity to think outside the box and develop unique solutions to the problems presented, which enhanced their learning in math and science. For instance, PST 8 remarked, "STEM PBL let me be creative with how I solved problems. We didn't have just one answer to find; we could try different things to see what worked". They particularly appreciated the ambiguity or ill-defined principles of the projects that encouraged them to experiment and use a trial-and-error approach. In this regard, PST 1 shared, "It was fun to come up with new ideas and test them out, especially when the solution wasn't obvious. It made me feel like I was doing something innovative". Similarly, PST 2 added, "I liked that we could think outside the box and try new ways to solve the problems. We didn't have to follow a set formula every time". Overall, the PSTs expressed that STEM PBL empowered them to approach problem solving creatively, using their intuition and innovative thinking rather than relying on pre-established formulas or procedures.

The following six themes emerged from the data for the second research question: What principles of STEM PBL instruction do PSTs plan to implement in their future classes?

3.7. Student Autonomy

The PSTs valued the independence that they experienced in STEM PBL projects, finding empowerment in their ability to make choices about how to approach problems and manage their work. They expressed a desire to provide this same autonomy to their future students. PST 7 noted, "I think the best part was having the freedom to explore different ideas and solutions. In my own class, I'd want my students to have that same independence to experiment and learn on their own". Similarly, PST 6 emphasized the importance of giving students control over their learning, stating, "I would love to give my future students more control over their learning, just like we had in PBL. It made learning more interesting when we could choose how we approached a project". PST 5 encapsulated the sentiments of her peers by explaining, "Giving students autonomy in the classroom allows them to find their own ways to solve problems, which I think leads to deeper learning". Overall, the PSTs recognized that fostering student autonomy not only enhances engagement but also promotes a deeper and personalized learning experience.

3.8. Inquiry-Based Learning

STEM PBL is centered around asking questions and seeking answers. The PSTs found that this inquiry-based approach fostered deep thinking and engagement with the material, and they expressed a desire to bring this questioning mindset into their own teaching. For instance, PST 8 remarked, "In my own classroom, I'd use inquiry-based learning like we did in PBL. It encourages students to think for themselves and discover answers". PST 2 highlighted the significance of questioning in inquiry-based learning during STEM PBL, stating, "I think asking questions was a big part of why I enjoyed PBL. I'd definitely want to use that in my teaching—letting students figure things out by asking questions, not just giving them the answers". Similarly, PST 7 noted, "The way we explored different problems through questions helped me learn better, and I want my future students to benefit from that too". These statements reflect that most PSTs emphasized the practice of encouraging student questioning as a key aspect of STEM PBL that they intended to implement in their future instruction.

3.9. Open-Ended Tasks

The open-ended nature of the tasks in STEM PBL allowed the PSTs to explore multiple solutions and approaches. They appreciated the flexibility of these tasks, which promoted creativity and personalized learning. For instance, PST 1 stated, "I really liked that there was no single right answer in PBL. I'd want my students to have the same experience where they can explore different solutions and do not feel limited by one approach". Similarly, PST 7 remarked, "The open-ended nature of PBL allowed me to think creatively and try different ways to solve problems. I'd love to give my students that kind of freedom". Additionally, the PSTs emphasized how open-ended tasks encouraged them to think critically, as illustrated by PST 3's comment: "I think having open-ended tasks is important because it helps students develop critical thinking skills. It forces them to come up with their own solutions, which is something I want to use in my future classrooms". Overall, they associated the openness of these projects with multiple solutions and personalized approaches, which enabled them to engage in critical and creative thinking throughout the project.

3.10. Collaboration and Teamwork

Collaboration was a cornerstone of the PSTs' STEM PBL experience, and they aspired to foster a similar collaborative environment in their own classrooms. They believed that teamwork enhanced learning and problem solving by bringing together diverse perspectives. For example, PST 2 stated, "I think collaboration is key to learning. In my class, I will definitely want my students working together on projects like we did in PBL because we learned so much from each other". Similarly, PST 4 emphasized, "I would prioritize group work in my class because students learn better when they collaborate, just like we did in the STEM PBL projects". Beyond working in groups, the PSTs highlighted the importance of sharing ideas as a whole class. PST 6 illustrated this point by saying, "The teamwork aspect of PBL was really helpful. I want to implement opportunities for students to share ideas as a whole class and work together toward a common goal". Overall, the PSTs' experiences in STEM PBL reinforced their belief in the value of collaboration, and they were committed to integrating this practice into their future teaching to enhance students' learning and engagement.

3.11. Integration of Technology

The PSTs appreciated the use of technology in solving problems and presenting their findings in STEM PBL projects. They aspired to incorporate technology into their teaching

to engage students and enhance learning. For example, PST 3 noted, "Using technology in PBL was a huge plus. I want to use the same tools, like simulations or data analysis software, to help my students solve problems and visualize concepts". Similarly, PST 2 reflected that technology was helpful for her to increase her engagement in the content, stating, "I think technology makes learning more engaging. I will definitely implement tech tools in my class, especially for simulations that bring science and math to life". Additionally, the PSTs emphasized that technology helped them to understand abstract or complex ideas more easily. PST 5 expressed this sentiment by saying, "In my future classes, I will use more technology because it helps students grasp complex concepts better, just like the tools we used during PBL". In brief, the PSTs' experiences with technology in STEM PBL not only enhanced their own understanding but also reinforced their commitment to using technological tools to foster student engagement and facilitate deeper learning in their future classrooms.

3.12. Real-World Relevance

The PSTs appreciated how STEM PBL connected classroom learning to real-life issues and scenarios. They expressed a desire to use real-world problems to make learning more meaningful for their future students, helping them to recognize the importance of math and science in everyday life. PST 8 remarked, "I'd love to bring real-world problems into my classroom, just like we did in PBL. It makes the learning more meaningful for students when they can see how it connects to real life". Similarly, PST 5 stated, "I want my future students to see how math and science apply to real life, so I'd definitely incorporate projects that focus on solving real-world issues". PST 2 summarized the importance of real-world relevance by saying, "What I liked about PBL was that it felt relevant to everyday life. That's something I'd want to bring into my classroom because students learn better when they can relate to what they are studying". In conclusion, the PSTs' emphasis on real-world connections highlights their commitment to creating meaningful learning experiences that demonstrate the relevance of math and science to their students' lives.

4. Discussion

Our findings revealed that pre-service teachers who participated in the STEM PBL-focused methods course identified several key principles of STEM PBL instruction that were beneficial to their own mathematics and science learning. Additionally, they noted specific aspects of STEM PBL that they wished to implement in their future teaching practices. Collaboration and real-life relevance were common themes across both research questions, emerging as essential principles of STEM PBL. While these two themes are clearly important, their prominence in the data does not suggest that they are inherently more valuable than other principles. All principles identified are equally significant if our goal is to provide students with a more holistic experience of STEM learning in the 21st century.

Other themes emerged exclusively from one research question—either in terms of which principles of STEM PBL were useful for the pre-service teachers' learning or which principles they wished to transfer to their future instruction. Interestingly, some principles that were identified as useful for learning did not re-emerge when the participants were asked what they intended to implement in their own classrooms. This discrepancy highlights the complementary, rather than mutually exclusive, nature of the principles, suggesting that pre-service teachers may use the principles of STEM PBL instruction interchangeably.

It is important to highlight that the teachers did more than simply mention the STEM PBL principles that they personally found helpful in understanding mathematics and

science. In addition to identifying these principles, they also contributed new ideas and additional principles that were not explicitly part of the initial framework but that they discovered to be valuable through their experiences with STEM PBL. One possible explanation for this could be that the pre-service teachers avoided redundancy by not repeating principles that they had already mentioned earlier. Another explanation aligns with Oleson and Hora's (2014) argument that teachers tend to teach in ways that reflect how they were taught. As a result, some of the principles that they found beneficial for their learning may not align with how they envision implementing STEM PBL in their future classrooms. For example, while hands-on learning emerged as a significant principle that helped the pre-service teachers to understand math and science concepts, it did not appear prominently in the data related to what they planned to implement in their future instruction. This could be due to the perceived complexity of effectively using hands-on tools in the classroom. The wide array of available tools (e.g., manipulatives) may require a level of expertise and confidence that teachers may not have developed during their training. Consequently, pre-service teachers may hesitate to plan lessons that rely on hands-on learning, despite acknowledging its value for their own understanding. Alternatively, the participants may have assumed that hands-on learning is such a fundamental aspect of 21st-century education that it did not need explicit mention. Regardless of this speculation, teacher educators must identify some indispensable tools that are necessary for teachers to feel confident in using them in their classrooms. These could include essential manipulatives (e.g., pattern blocks) that teachers must be equipped with while teaching mathematics and science, enabling them to integrate such tools seamlessly into their future instruction.

Another plausible explanation is related to the way that the research question was framed. The pre-service teachers were not simply asked to list all the principles that they found useful, but to thoughtfully reflect upon and share only the ones that they were most eager to implement in their future classrooms. This aligns with the research of Lev-Zamir and Leikin (2013), who pointed out that there is often a mismatch between what teachers say that they value and what they actually do in practice. This conflict may have surfaced in our study because we asked the participants to reflect on both what worked for them and what they planned to implement, rather than solely focusing on how mathematics and science should be taught. It is likely that the principles that the pre-service teachers listed were those that they were most confident about implementing in their future instruction, while the principles that they did not mention were those that they were less certain about incorporating into their practice.

It is also important to note that the pre-service teachers mentioned several vital principles of STEM PBL, such as open-ended tasks, that they wished to implement in their future classrooms. This finding underscores the transferability of these principles to their future instructional practices. Therefore, whether teacher educators adopt STEM PBL or other innovative instructional methods, they should emphasize these principles, as they have been shown to be effective in fostering student learning in student-centered classrooms (Noble et al., 2020). A key implication of this study is the need to emphasize all principles of STEM PBL in pre-service teacher education (Li et al., 2023). This will enable pre-service teachers to view these principles not only from a student's perspective but also from a teacher's perspective. Rather than focusing solely on STEM PBL as a comprehensive method, teacher educators could spotlight specific principles of STEM PBL in different projects or over several weeks. At the end of the course, modeling STEM PBL holistically can help pre-service teachers to understand how the various principles are interrelated and complementary, ensuring the successful implementation of projects and the achievement of well-defined learning outcomes.

One criticism of STEM PBL is that, while it has the potential to develop students' 21st-century skills, such as communication, collaboration, and creative thinking, its effectiveness in enhancing students' understanding of science and mathematics remains uncertain (National Academies of Sciences, Engineering, and Medicine (NASEM) (2021); National Research Council (NRC) (2012); Next Generation Science Standards (NGSS) (2023); Strobel & Van Barneveld, 2009). Noble et al. (2020) addressed this concern by emphasizing the importance of "incorporating rigorous content into PBL experiences, particularly by planning projects around discipline standards to ensure that appropriate content learning occurs" (p. 12). Our study supports this view, as the PSTs in the present study connected the principles of STEM PBL, including the development of skills like creative thinking, with targeted science and math standards. In this study, we designed the projects with well-defined outcomes and ill-defined tasks, providing the PSTs with opportunities to not only foster their future students' 21st-century skills but also improve their understanding of science and mathematics concepts. This was achieved by specifying the standards that students would meet through particular projects. This approach highlights a key aspect of STEM PBL when implemented in pre-service teacher courses: PSTs must view it from both the students' and teachers' perspectives. Teachers need to carefully integrate innovative instructional practices while ensuring that essential skills and knowledge are effectively covered by the end of the project. This approach offers PSTs a more realistic experience in planning STEM PBL lessons that not only help students to develop content knowledge in specific STEM fields but also provide meaningful learning opportunities.

Finally, the themes that emerged from our data revealed that when STEM PBL was incorporated into mathematics and science methods courses, the PSTs had the opportunity to observe essential characteristics of STEM PBL instruction. They identified many key elements of STEM PBL found in the literature, such as being "student-centered and driven, often including group work, interdisciplinary, and closely connected to the real world" (Noble et al., 2020). Interestingly, almost all of these principles, such as collaboration, which are widely discussed in the literature (Savery, 2006; Torp & Sage, 2002), were noted by the PSTs in this study. This demonstrates that the PSTs were able to grasp the holistic nature of innovative instruction through STEM PBL, viewing it both as students and as future teachers. The implication of this study is that PSTs need to observe the essential characteristics of innovative instructional practices from both the student and teacher perspectives. This dual perspective allows them to understand how these approaches benefit students and helps them to develop the skills to create effective instruction. By incorporating several of these key principles, PSTs can provide students with opportunities not only to develop 21st-century skills, such as collaboration, but also to deepen their science and mathematics content knowledge.

A limitation of this study is that we did not measure whether the PSTs' mathematics- or STEM-related content knowledge and pedagogical content knowledge changed after participating in the STEM PBL-focused mathematics methods course. A potential future direction for research would be to employ a mixed-methods study to investigate how PSTs' content knowledge and pedagogical content knowledge evolve while also observing the STEM PBL practices that they choose to implement in their classrooms. Such a study would provide a more comprehensive understanding of the impact of STEM PBL on both teachers' knowledge and their instructional decisions. Additionally, the participants were familiar with both the instructor and the interviewer, which might have introduced potential biases, as they had interacted with them during the course. While this familiarity may have introduced potential biases, measures were taken to minimize their influence on the data analysis by maintaining a clear distinction between the instructional responsibilities and the

research processes. This approach aimed to ensure that the findings authentically reflected the participants' experiences with STEM PBL.

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