

Engaging Young Learners in STEM through Virtual Reality and Hands-on Activities: A Case Study in Primary Classrooms

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ABSTRACT

This study explores how immersive, inquiry-based STEM education, supported by virtual reality (VR), can enhance primary students' learning experiences, behaviors, and interdisciplinary understanding. Thirty-six students (Grades 1–5) participated in 31 curriculum-aligned STEM activities designed around real-world problems, integrating science, technology, engineering, and mathematics through hands-on and VR-enhanced tasks. Using a qualitative case study design, data were collected through classroom observations, student work samples, interviews, and reflective feedback. The findings reveal strong student engagement, a deepening understanding of STEM integration, and the emergence of an eight-step learning cycle characterized by iterative problem-solving and collaboration. This study makes a theoretical contribution to inquiry-based and self-regulated learning models, providing practical guidance for educators and policymakers seeking to implement scalable, immersive STEM learning environments. Future directions highlight the potential of personalized learning systems to support adaptive and reflective STEM engagement.

KEY WORDS: Inquiry-based learning, primary science, STEM education, virtual reality

INTRODUCTION

In recent decades, STEM education, integrating science, technology, engineering, and mathematics, has emerged as a key priority in educational reform worldwide. As nations respond to the demands of rapidly evolving technological landscapes, STEM is increasingly recognized as a catalyst for economic competitiveness, innovation, and national development (Bybee, 2010). Countries such as the United States, Finland, Singapore, South Korea, and Australia have adopted comprehensive STEM policies to cultivate inquiry, creativity, problem-solving, and digital literacy from early childhood to secondary education. These efforts align with the UNESCO 2030 Agenda for Sustainable Development, which calls for inclusive, future-ready education that prepares learners to engage with real-world challenges through interdisciplinary knowledge and skills. Central to these global efforts is a shift away from isolated subject instruction toward integrated, project-based, and student-centered STEM approaches (AlAli, 2024). In many educational systems, including Thailand's, STEM integration is positioned as a national reform strategy to enhance workforce readiness, scientific literacy, and innovation capacity (IPST, 2015; Promboon et al., 2018). Within this context, a growing body of research explores effective STEM implementation models, especially those grounded in inquiry-driven and collaborative learning. Increasingly, these models incorporate emerging digital tools, such as virtual reality (VR), to promote engagement, spatial reasoning, and deeper understanding, particularly in science and engineering

education (Chang et al., 2020). These innovations offer promising directions for enriching STEM learning experiences and better aligning instruction with the skills required in the 21st-century knowledge economy.

Although global efforts to promote STEM education exist, several challenges remain in effectively translating policy into classroom practice, particularly at the primary education level. Many existing studies have focused on secondary or tertiary education, leaving a relative gap in understanding how integrated STEM approaches can be developmentally appropriate and pedagogically effective for younger learners (De Loof et al., 2021; English, 2016). In contexts like Thailand, while national frameworks encourage STEM integration, teachers often lack concrete models, instructional resources, or professional development support needed to implement STEM activities in line with the curriculum (Changtong et al., 2020). Furthermore, although the use of emerging technologies such as VR has shown promise in enhancing student engagement and conceptual understanding (Merchant et al., 2014), their application in early STEM education remains underexplored. There is limited empirical research examining how VR tools can be meaningfully embedded into inquiry-based STEM activities in primary school classrooms, especially within developing countries or rural educational contexts (Akçayır and Akçayır, 2017). In particular, few studies have investigated how VR and kinesthetic learning environments can facilitate collaboration, iterative design thinking, and real-world problem-solving in young learners,

while simultaneously aligning with national science standards. These gaps highlight the need for practical, classroom-tested models that demonstrate how STEM education can be adapted for primary-level learners, leveraging immersive technologies and fostering 21st-century competencies within localized curriculum frameworks. By addressing this gap, it is suggested that educators and policymakers can better support early and equitable STEM engagement, which is essential for nurturing scientific literacy and innovation from the earliest years of schooling (Stylianidou et al., 2018).

This study addresses challenges in STEM integration by proposing a structured model of primary science instruction enhanced with immersive technologies. The approach combines kinesthetic, play-based learning in a dedicated STEM room with hands-on experimentation and collaboration, aligned with Thailand's national science curriculum for relevance. To deepen engagement and conceptual understanding, VR tools enable learners to explore abstract concepts, such as space, energy, and ecosystems, in multisensory environments (Johnson-Glenberg et al., 2023; Ding and Cha, 2024). Emphasizing collaboration, creativity, and inquiry, the framework offers a scalable, developmentally appropriate model for early-grade and under-resourced STEM education.

This study aims to evaluate the effectiveness of the proposed STEM-VR-integrated instructional model in promoting interdisciplinary learning, science process skills, and student engagement in a primary school context. Through a qualitative research design, the study collects and analyses student work samples, classroom observations, video recordings, and in-depth interviews to capture both observable outcomes and learner perceptions. The approach is grounded in the real-world experiences of young learners in a primary school and reflects a commitment to evidence-based STEM education practices that are developmentally appropriate, technologically enriched, and curriculum-aligned. Therefore, to systematically assess the benefits of the proposed activities, the study addresses the following research questions:

- RQ1: How do primary students experience and respond to STEM activities integrating hands-on learning and VR?
- RQ2: What behavioral and collaborative patterns emerge during students' participation in immersive STEM learning?

By exploring these questions, the ultimate goal of this study is to generate insights into how immersive, iterative, and curriculum-based STEM instruction can enrich primary science education. The findings contribute to future curriculum development, instructional design, and policy directions for advancing STEM education at the foundational levels of schooling, both in Thailand and in comparable international contexts.

LITERATURE REVIEW

STEM Education and Curriculum Integration in Primary Schools

Integrated STEM education refers to an interdisciplinary approach that merges science, technology, engineering, and

mathematics into cohesive learning experiences that emphasize real-world problem-solving (Bybee, 2010; Johri et al., 2013). Unlike teaching subjects in isolation, integration promotes the application of knowledge across domains, encouraging critical thinking, innovation, and inquiry. Curriculum integration involves aligning STEM activities with educational goals and assessment frameworks to ensure coherence (Kelley and Knowles, 2016). When well-designed and integrated, STEM curricula connect classroom learning with everyday contexts, fostering both cognitive and practical competencies.

Globally, many systems embed STEM in primary curricula to cultivate 21st-century skills early. The United States, Australia, Singapore, and South Korea have developed national frameworks emphasizing project-based learning, student-centered instruction, and real-world relevance (Honey et al., 2014; Bybee, 2013). In Thailand, the Institute for the Promotion of Teaching Science and Technology (IPST) has advanced STEM education by encouraging integration across science curricula, with activities highlighting engineering design, problem-solving, and interdisciplinary thinking (Institute for the Promotion of Teaching Science and Technology, 2015). It aims to create continuity between scientific content and practical applications in the early grades.

Research increasingly supports the integration of STEM at the primary level. English (2016) reported that integrated STEM activities enhanced students' ability to transfer knowledge across subjects, leading to stronger conceptual understanding in mathematics and science. Similarly, Le et al. (2023) found that participation in interdisciplinary STEM projects fostered engagement, creativity, and problem-solving skills. In Thailand, Promboon et al. (2018) emphasized that STEM activities must be age-appropriate and curriculum-aligned but observed that effectiveness varied with teacher readiness and instructional support. Collectively, these studies demonstrate the potential of curriculum-aligned STEM integration to enhance learning, particularly when instruction is structured and linked to students' lived experiences.

Despite these benefits, challenges persist in implementing integrated STEM in primary classrooms. Teachers often struggle to design interdisciplinary activities that align with curricular standards while remaining developmentally suitable for young learners (Estapa and Tank, 2017). Moreover, accessible, evidence-based models for STEM integration in early education remain scarce, particularly in contexts with limited resources or professional development opportunities. These barriers highlight the need for instructional frameworks that not only align with national curricula but also engage students through inquiry-driven, collaborative, and hands-on learning experiences.

Inquiry-based and Technology-enhanced STEM Learning

Inquiry-based learning emphasizes students' active engagement through questioning, exploration, experimentation, and reflection. In STEM, it encourages learners to investigate authentic problems, develop hypotheses, test ideas, and

construct evidence-based explanations (Barron and Darling-Hammond, 2008; Hmelo-Silver et al., 2007). This approach fosters conceptual understanding alongside cognitive and metacognitive skills such as reasoning, evaluation, and self-regulation. Unlike traditional teacher-led methods, inquiry-based STEM positions students as knowledge constructors, exposing them to the iterative and uncertain nature of scientific and engineering practices.

Educational technologies have expanded the scope of inquiry-based STEM instruction. Simulations, robotics, and VR enable students to interact with phenomena that are often inaccessible in conventional classrooms (Radianti et al., 2020). VR provides immersive, interactive experiences that enhance engagement, spatial reasoning, and the visualization of abstract processes such as planetary motion or molecular interactions (Tene et al., 2024; Yang et al., 2024; Hu-Au, 2024; O'Connor et al., 2019). These tools enrich inquiry by enabling safe experimentation, providing immediate feedback, and allowing for the meaningful manipulation of virtual objects, thereby supporting deeper scientific reasoning and motivation.

Empirical studies confirm the value of combining inquiry with immersive technologies. Zang et al. (2022) demonstrated that project-based learning with VR enhanced learning performance, with mental health and immersion serving as mediating factors. Van der Meer et al. (2023) found that collaborative inquiry in virtual environments strengthened peer interaction and inquiry cycles. However, most studies focus on secondary or higher education, with limited evidence on adapting immersive inquiry-based STEM approaches for primary learners and aligning them with national curricula. Despite clear benefits, effective implementation in primary contexts requires careful consideration of developmental appropriateness, curricular alignment, and classroom realities. Teachers often lack sufficient training, time, or resources to adopt these methods. Thus, age-appropriate instructional frameworks that integrate inquiry, technology, and curricular objectives in structured formats are essential (Kamarudin et al., 2022; Stringer et al., 2022; Fernández-Sánchez et al., 2022).

Student Engagement and 21st Century Skills in STEM

STEM 21st-century skills encompass critical thinking, communication, collaboration, creativity, and digital literacy, which are essential competencies for thriving in today's complex and global environment (Care et al., 2024). In STEM education, these are not add-ons but core outcomes embedded in learning. Instruction that integrates real-world problem-solving, teamwork, and digital tools provides authentic contexts for developing future-ready competencies (Lee et al., 2024). Student engagement is both a prerequisite for and an outcome of STEM learning. Engagement is multidimensional, comprising behavioral, cognitive, and emotional aspects (Fredricks et al., 2004; Wang and Eccles, 2014). Hands-on tasks, inquiry, and real-life applications foster persistence and deeper knowledge retention. Active methods such as project-

based learning, collaborative inquiry, and technology-rich exploration significantly enhance engagement in primary STEM education (Le et al., 2023; Steiner et al., 2024). Such environments promote ownership, intrinsic motivation, and self-efficacy.

Digital technologies further enhance these skills by creating immersive and engaging environments. VR enables learners to visualize complex concepts, collaborate in shared spaces, and engage in simulated problem-solving (Ding and Cha, 2024). These tools foster creativity, teamwork, and metacognitive awareness – skills essential for lifelong learning and innovation (Johnson-Glenberg et al., 2023). Kinesthetic and play-based digital tools also sustain attention and engagement, making them especially effective for young learners (Miller, 2018; Aloizou et al., 2024). Despite this potential, many STEM programs lack structured pedagogical models to guide teachers in systematically cultivating 21st-century skills. Primary learners require developmentally appropriate scaffolds that strike a balance between challenge and support, enabling collaboration, reflection, and iteration in authentic contexts. Without clear frameworks, opportunities to fully integrate engagement and future-ready skills into early STEM education remain underutilized.

THE PROPOSED STEM LEARNING ACTIVITIES




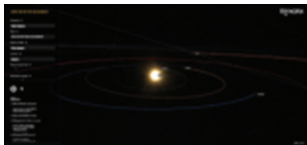
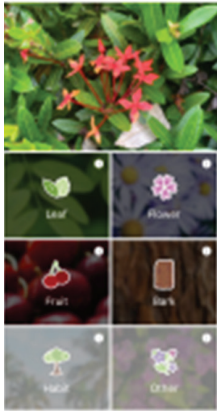
The design of the 31 STEM activities was grounded in well-established educational theories. The integration of STEM domains was informed by interdisciplinary teaching frameworks (Hallström and Ankiewicz, 2023), while the structure of each activity followed principles of inquiry-based and design-oriented learning. Additionally, the activities were designed to develop 21st-century skills such as collaboration and creativity, with selected activities incorporating VR based on evidence supporting immersive learning for motivation and conceptual understanding (Makransky and Lilleholt, 2018). These combined theoretical perspectives supported the creation of a coherent, developmentally appropriate learning environment for primary students.

Building on the theoretical foundation presented in the literature, this study proposed a structured set of 31 STEM activities designed to operationalize with the Thai primary science curriculum. These activities were developed to support inquiry-based, interdisciplinary learning experiences that align with national science standards while integrating technology, particularly VR, and hands-on design elements. The instructional model addresses the need for curriculum-aligned, developmentally appropriate STEM learning tools that foster 21st-century skills in young learners. By embedding scientific inquiry, engineering design, mathematical reasoning, and technological applications into age-specific tasks, the activities aim to provide a scalable and adaptable approach for immersive STEM instruction. All 31 activities were designed and organized

into 4 categories based on themes, including physical sciences, biological sciences, earth and space sciences, and technology. The activities varied in format, combining kinesthetic learning, multimedia resources, and immersive VR experiences to enhance engagement and conceptual understanding. The examples of the activities, including






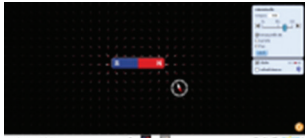
their titles, targeted science topics, learning objectives, and tools used, are provided in Table 1. The table illustrates the instructional design logic behind each activity and shows how content standards were translated into authentic STEM activities. These activities provided the core structure of the learning environment evaluated in this study. To explore

Table 1: Examples of the STEM activities

Activity title	Science topic	Learning objective	Main materials
1. Fingerprint's spy 	Genetics	<ul style="list-style-type: none"> • Understand the basic fingerprint patterns: loop, whorl, and arch. • Learn how to collect and analyze fingerprints using basic tools and technology. 	Graphite powder White index cards or fingerprint recording sheets USB digital microscope Fingerprint classification chart
2. Why Does the Sky Change Color? A Light Scattering Experiment? 	Light	<ul style="list-style-type: none"> • Understand the principle of light scattering in the atmosphere. • Explain why the sky appears blue during the day and red-orange during sunset. 	Flashlight (white LED is ideal); Translucent glue stick
3. Water Bottle Rocket 	Force	Understand Newton's Laws of Motion.	Plastic bottles Rubber stopper Water Cardboard
4. Exploring the Solar System with Technology 	Solar system	Understand the components and scale of the solar system.	Computers or tablets with internet access; Simulation software Model Solar System
5. Tech Botany ← Choose related organ 	Plant	Learn how to classify plants based on physical and scientific characteristics.	Smartphones or tablets with plant identification apps (e.g., PlantNet, PictureThis, iNaturalist, Google Lens)

(Contd...)

Table 1: (Continued)

Activity title	Science topic	Learning objective	Main materials
6. Virtual Geologist 	Soil, Rocks, and Minerals.	Understand the types, formation, and distribution of soil, rocks, and minerals.	Google Earth VR Rock Hound VR
7. Exploring the Human Body Systems Through Augmented Reality 	Body System	Understand the structure and function of major human body systems (e.g., circulatory, respiratory, digestive, nervous, skeletal)	Smartphones or tablets AR apps
8. Ecosystem Explorer: A Virtual Reality Journey 	Ecosystem	To understand the relationships between organisms, their environment, and ecological balance.	Ecosphere VR; National Geographic Explore VR
9. Frog Guiro Sounds 	Sound	Understand how the size and shape of an object affect the frequency and pitch of sound.	Wooden frog guiro toys of at least 3 different sizes
10. Wind Turbine 	Electricity	Understand the principles of wind energy and how wind turbines generate electricity.	Wind turbine kit Microcontroller boards. Robotics kit
11. Magnetic Tech Lab 	Magnets	Understand magnetic fields, attraction, repulsion, and electromagnetism.	Digital simulation tools (e.g., PhET Simulation: "Magnets and Electromagnets") Smartphones or tablets magnets

how the activities influenced students' learning outcomes, engagement, and behavioral patterns.

RESEARCH METHODOLOGY

Participants

The participants in this study were 36 primary school students (Grades 1-5) enrolled at a school located in southern

Thailand. The students participated voluntarily, with parental consent, and were selected based on their enrollment in the school's designated STEM learning program. The age range of the students was approximately 6–11 years. The school was chosen due to its implementation of a dedicated STEM classroom and its support for curriculum-aligned technology integration. The class composition reflected a mixed-ability

group, and no prior experience with VR technology was required or assumed.

Measuring Tools

Multiple qualitative data sources were used to capture students' perceptions of learning and their behavioral patterns while engaging with immersive STEM activities, as follows:

- Student work samples included science notebooks, worksheets, and engineering design artifacts (e.g., blueprints and prototypes) produced during the activities. They provided insight into students' reasoning, problem-solving processes, and task completion.
- Observational protocols and video recordings: Researchers conducted systematic classroom observations and recorded group activities. A structured checklist and narrative field notes documented student behaviors, interaction patterns, collaboration, and emotional responses during learning tasks.
- In-depth interviews and reflective questions: Semi-structured interviews were conducted with 12 purposively selected students (three from each grade level) to explore their perceptions of STEM learning, interdisciplinary connections, and their experiences using VR. Additionally, all 36 participating students participated in reflective sessions following the completion of the 31 integrated STEM activities. During these sessions, students were encouraged to articulate their understanding of the four STEM disciplines, Science, Technology, Engineering, and Mathematics, and how these disciplines are interconnected in real-world contexts. Open-ended prompts such as *"What is your favourite thing about the STEM room?"* and *"What is your favourite part of STEM? Science, Technology, Engineering, or Mathematics?"* were used to elicit personal preferences, motivations, and conceptual integration. These data helped provide a richer understanding of how students perceived the value and relevance of the STEM learning experience.
- VR experience feedback: Informal written reflections and open-ended survey items were used to capture students' impressions of using VR technology in learning, including its usability, emotional engagement, and contribution to understanding abstract concepts.

Research Design

This study employed a qualitative case study design to investigate how immersive STEM activities influenced students' experiences and behaviors in a real-world classroom. The instructional intervention consisted of 31 hands-on, curriculum-aligned STEM activities implemented over a 6-week period. The activities integrated inquiry-based and design-oriented learning processes, with select tasks enhanced through VR to support conceptual visualization. Students were arranged into nine mixed-grade groups of four and engaged collaboratively in designing and testing solutions to real-world problems. The teacher researcher served as a facilitator, supporting inquiry, documenting interactions, and guiding reflective discussions.

Data Analysis

A thematic analysis approach was used to analyze data, focusing on students' learning behaviors and their perceptions of the immersive STEM experience, as follows:

- Transcription and coding: Observational notes and interview transcripts were transcribed and coded. Initial codes were generated inductively, capturing patterns related to engagement, collaboration, inquiry, and affective responses to VR.
- Theme development: Codes were grouped into broader thematic categories such as "problem-solving behaviors," "collaborative strategies," "technology-enhanced motivation," and "emergent inquiry cycles."
- Triangulation: Multiple data sources, including interviews, observations, and student work, were cross-checked to ensure consistency and credibility of findings.
- Interpretation: Final themes were interpreted in light of the research questions and theoretical perspectives on STEM integration, inquiry-based learning, and immersive educational technologies. This interpretive process reflected recurring behavioral and collaborative patterns observed throughout the activities.

RESULTS

This section presents findings in response to the two research questions. The analysis draws on triangulated data from classroom observations, student work, video recordings, and interviews.

Students' Perceptions of STEM Learning and VR Integration

Regarding RQ1, thematic analysis of interviews and reflective responses revealed three major patterns in how students perceived and responded to the immersive STEM learning experiences: (1) strong preference and motivation toward technology, especially VR; (2) evidence of interdisciplinary understanding across STEM domains; and (3) perceived benefits of technology-enhanced learning for deeper conceptual engagement.

Student preferences and engagement

A significant proportion of students (90%) identified Technology, particularly the use of VR, as their favorite component of the STEM experience. VR-based activities were frequently described as challenging, exciting, and immersive, with students highlighting the novelty and interactivity of exploring abstract content through 3D simulations. One student remarked, *"I felt like I was really inside the solar system when using VR. It helped me understand space better than any textbook."* The hands-on, experiential nature of VR seemed to create learning environments that students found both enjoyable and memorable.

Interdisciplinary understanding of STEM

In addition to their preferences, students demonstrated a conceptual understanding of the interconnected nature of

STEM disciplines. Many were able to articulate how they applied knowledge across subjects to solve real-world problems. For example, a Grade 5 student explained, “*We used science to learn about energy, math to measure how much we needed, engineering to build a model car, and technology to test it. Everything worked together.*” These responses demonstrated students’ growing ability to transfer and integrate knowledge, as well as their awareness of how different disciplines support one another in solving authentic challenges.

Technology as a catalyst for deeper learning

Students consistently viewed technology, particularly VR, not just as engaging, but as instrumental to their understanding of difficult STEM concepts. They reported that immersive simulations helped them visualize invisible processes, explore abstract ideas, and test their designs in meaningful ways. Several students mentioned that using VR made science “*easier to understand*” and “*more real.*” Others commented on how building and testing models using both physical materials and digital tools helped them improve their ideas and learn from mistakes.

Observed Learning Behaviors and Collaborative Patterns

Regarding RQ2, during their participation in the STEM activities, students exhibited a range of learning behaviors that reflected curiosity, engagement, and collaborative inquiry. At the individual level, many students demonstrated increasing levels of persistence and initiative as they encountered design challenges and problem-based scenarios. Rather than giving up, students often revisited earlier ideas, modified their approaches, and expressed pride in their creative outputs. In group contexts, collaborative patterns emerged as students assumed different roles, such as planner, builder, tester, or presenter, while negotiating responsibilities and supporting one another through discussion and peer feedback. Communication among group members was frequent and purposeful, often

focused on clarifying task goals or refining prototypes based on test results. These interactions suggest that the integrated STEM environment supported the development of teamwork, negotiation skills, and collective problem-solving. Additionally, students exhibited visible signs of metacognitive behavior: they asked reflective questions about their own processes, monitored the effectiveness of their designs, and self-corrected based on outcomes. This blend of self-directed and socially shared regulation points to an emerging capacity for self-regulated learning, even among younger learners.

These behavioral patterns laid the foundation for a recurring structure that students organically followed across the learning tasks, leading to the emergence of a distinctive eight-step learning cycle, as shown in Figure 1.

As shown in Figure 1, a consistent behavioral pattern emerged throughout the implementation of the 31 STEM activities across all student groups. Rather than progressing through tasks in a strictly linear fashion, students exhibited a recurring set of actions and interactions that coalesced into an eight-step learning cycle. This cycle, refined through observation and analysis, became the foundation of the STEM 8-Step Framework, reflecting students’ natural progression through inquiry, design, iteration, and reflection. Each phase is described below, along with illustrative behaviors drawn from classroom observations.

1. Identify a problem: Students began by identifying a real-world problem within the context of each activity. This phase involved making observations, raising questions, and brainstorming issues related to their environment. This step laid the foundation for inquiry and stimulated curiosity.
2. Understand the problem: Once a problem was defined, students explored it more deeply by discussing relevant scientific concepts, examining causes, and analyzing contextual factors. This phase promoted critical thinking



Figure 1: Learning behaviors and collaborative patterns during STEM activities

and helped students establish a conceptual foundation for solving the problem.

3. Ideate and create: During this phase, students engaged in group brainstorming to generate potential solutions. All group members were encouraged to contribute ideas, leading to collaborative creativity and the selection of the most promising approach.
4. Design a solution: Selected ideas were translated into concrete plans. Students sketched blueprints, selected materials, identified constraints, and sequenced construction steps. This stage emphasized structured planning and design thinking.
5. Build a prototype: Students constructed their designs using the provided materials. Collaborative teamwork was evident as students divided roles, supported one another, and adapted their constructions based on emerging needs and feedback.
6. Test the solution: Prototypes were tested to determine their functionality and effectiveness. Students observed outcomes, collected data, and identified areas for improvement. The testing phase often revealed flaws, leading to further refinement of the solution.
7. Group collaboration and analysis: Instead of proceeding directly to final presentations, students often revisited earlier stages, especially when their initial solutions failed. Groups critically analyzed results, discussed shortcomings, and returned to the ideation or design phase. For example, one group redesigned a bridge after its structure failed under testing. Through group discussion and redesign, they improved the prototype and successfully met the activity's goals. This iterative behavior highlighted students' persistence and reflective thinking.
8. Presentation: In the final phase, students presented their work to peers and teachers. Presentations included descriptions of the design process, explanations of the scientific concepts applied, and reflections on the challenges and solutions encountered. This phase encouraged communication skills and promoted ownership of learning outcomes.

DISCUSSION

Students' Perceptions of STEM Learning and VR Integration (RQ1)

The study found that students expressed high levels of enjoyment, motivation, and conceptual engagement when participating in STEM activities that integrated hands-on exploration with immersive VR experiences. This result confirms the core assumption of constructivist learning theory (Vygotsky, 1978): that students learn best when they actively build knowledge through experiential interaction with their environment. What distinguishes the 31 proposed activities is their dual-modality structure: each activity combined physical, manipulable components (e.g., Virtual Geologist) with digital immersion through VR (e.g., Google Earth VR). This fusion of tactile and immersive experiences created a

rich learning ecosystem where students could visualize abstract scientific phenomena and immediately apply that understanding through project-based creation.

Students' responses revealed growing awareness of how science, technology, engineering, and mathematics work together to solve real-world problems. Many identified technology, especially VR, as the most exciting and useful element, not only for enjoyment but also for helping them grasp concepts that traditional instruction made difficult (Makransky and Petersen, 2021). Their reflections align with the goals of integrated STEM education, which seeks to dissolve disciplinary boundaries and situate knowledge within meaningful contexts (Le et al., 2023; Xie and Zhang, 2024). Importantly, the 31 STEM activities were not isolated tasks but rather scaffolded experiences that spanned multiple domains and grade levels, allowing students to revisit core concepts (e.g., energy, force, materials) through different lenses. This spiraling design, paired with interdisciplinary integration, contributed to sustained student interest and deeper learning. Moreover, the use of student-centered questions, reflection prompts, and opportunities for self-expression within each activity encouraged metacognition and autonomy. It aligns with Vygotsky's (1978) Zone of Proximal Development (ZPD), where students benefit from scaffolded support but are encouraged to extend their learning through guided discovery.

Observed Learning Behaviors and Collaborative Patterns (RQ2)

Behavioral analysis during the STEM activities revealed that students consistently engaged in an iterative, inquiry-based learning cycle, which organically formed into an eight-step learning framework. Rather than following rigid sequences, students returned to earlier phases, especially ideation, testing, and analysis, demonstrating resilience, reflective thinking, and collaborative decision-making. The emergence of this eight-step cycle is strongly grounded in the principles of problem-based and design-based learning (Xie and Zhang, 2024; Çavuş et al., 2025). Students were not merely executing predetermined tasks but were actively engaging in scientific inquiry, engineering design, and peer dialog – skills central to authentic STEM practices.

A unique feature of the 31 STEM activities was their embedded design for failure and iteration. Each activity encouraged students to prototype, test, analyze results, and refine their designs. For example, in the bridge-building activity, groups revised their designs after test failures, using peer feedback and concept review to improve their models. This structure promoted the kind of productive struggle that scholars argue is essential for deep learning and adaptive problem-solving. Furthermore, the activities deliberately required role distribution and group coordination. Students took on responsibilities such as data recorder, model builder, or presenter, which facilitated ownership of the process and emphasized the social dimension of learning. The peer negotiation and group decision-making observed reflected real-world engineering

team dynamics, supporting the development of communication and interpersonal skills (Pattison et al., 2023).

Another defining characteristic of the 31 activities was their alignment with Thai national science standards, ensuring both curricular relevance and pedagogical innovation. The activities maintained a balance between structure and flexibility, providing clear goals and materials, while allowing freedom in design decisions and solution strategies. This balance empowered students to explore, make mistakes, and refine their thinking within safe but challenging learning conditions. Taken together, the structured design of the 31 activities, grounded in inquiry, integration, collaboration, and iteration, enabled students to exhibit expert-like behaviors in a primary education setting. The emergence of the eight-step learning cycle not only reflects their behavioral growth but also offers a practical model for future STEM educators aiming to implement immersive, interdisciplinary approaches in the classroom.

IMPLICATIONS

Theoretical Implications

Grounded in constructivist learning theory (Vygotsky, 1978), the study affirms the principle that learners actively construct meaning through hands-on, context-rich experiences. The integration of VR in the 31 STEM activities enhanced this process, providing visual and spatial representations of abstract scientific concepts that facilitated conceptual construction (Guisasola and Zuza, 2025). The iterative, student-driven nature of the activities aligns closely with the tenets of inquiry-based learning (Usable STEM model; Integrated STEM review) (Usable STEM, 2023; Seprie et al., 2025), which emphasize exploration, questioning, and reflection as foundational to knowledge building. By documenting how students navigated the learning process, often looping between ideation, testing, and revision, the study contributes to an expanded view of inquiry, one that is recursive and socially constructed. The observed eight-step learning cycle adds nuance to existing models of inquiry and engineering design by embedding the reality of failure, iteration, and collaborative analysis into the learning trajectory. It supports and extends work from studies on design-based learning, adding a practical behavioral framework for early STEM education (Sung and Kelley, 2019).

Moreover, this research adds to the growing body of evidence that immersive technologies, particularly VR, can meaningfully enhance the cognitive and emotional dimensions of learning (Wu et al., 2023; Zhang et al., 2024). The study contributes theoretically by illustrating how VR, when used in combination with physical construction tasks and interdisciplinary inquiry, serves not merely as a motivational tool but as a cognitive amplifier, enabling young learners to grasp spatial and abstract concepts otherwise difficult to visualize.

The findings support the theory that technological mediation in learning can extend the learner's zone of proximal development (Vygotsky, 1978). By scaffolding students' conceptual understanding through simulation and interaction, VR

enabled deeper engagement with content and facilitated more meaningful participation in STEM problem-solving processes.

Practical Implications

The findings from this study yield several practical implications for the design, implementation, and policy development of STEM education in primary schools. The integration of real-world problem-solving, hands-on construction, and immersive technology through the 31 STEM activities provides a replicable model for enhancing student engagement and interdisciplinary learning from an early age.

For classroom practitioners, this study offers a concrete instructional model, the eight-step learning framework that supports inquiry, creativity, iteration, and collaboration. Teachers can use this framework to guide students through STEM problem-solving processes in a structured yet flexible manner. The activities emphasize learning by doing, peer interaction, and reflective analysis, which align with contemporary goals for 21st-century skill development. The findings also suggest that immersive technologies, such as VR, can be leveraged effectively even in primary classrooms, provided they are embedded within coherent learning tasks. Teachers are encouraged to move beyond using technology as a novelty and instead use it as a cognitive and exploratory tool to enrich students' conceptual understanding.

Additionally, the emphasis on collaborative group work and role-based responsibilities offers a classroom management strategy that promotes inclusion and differentiated learning. Educators can adapt these approaches to various content areas and grade levels to increase student motivation and ownership of learning.

Moreover, curriculum developers can draw on the structure and diversity of the 31 STEM activities as a model for designing integrative units that blend science, mathematics, engineering, and technology. Each activity in this study was aligned with Thai national curriculum standards, demonstrating that STEM learning can be meaningfully integrated without replacing existing content, but rather enriching it through interdisciplinary applications. Designers should consider embedding opportunities for iteration and reflection within STEM units to mirror the real-world practices of engineers and scientists. Furthermore, the observed behavioral learning cycle, spanning from problem identification to group analysis and presentation, can serve as a guiding structure for the development of age-appropriate STEM modules that foster both content knowledge and process skills. The study also highlights the importance of integrating scaffolding technology, ensuring that digital tools, such as VR, are not standalone features but are meaningfully linked to curricular goals and hands-on tasks.

LIMITATIONS AND FUTURE RESEARCH

This study provides valuable insights into the design and implementation of immersive STEM learning in primary

education; however, several limitations should be noted. First, the research was conducted in a single school with a relatively small group of students from Grades 1 to 5, which limits the generalizability of the findings. Although the mixed-age classroom provided opportunities for collaboration, variations in developmental stage, prior knowledge, and language skills may have influenced engagement and outcomes in ways not systematically controlled. Second, the study relied primarily on qualitative methods – such as observation, interviews, and student artifacts – without pre- and post-assessments of content knowledge or skills. Thus, while the behavioral and perceptual data are robust, claims regarding academic achievement and long-term retention remain exploratory. Third, although the 31 STEM activities were aligned with curriculum standards and incorporated VR-based components, the broader scalability of such technology-rich environments may be constrained by resource access, teacher training, and infrastructure support.

These limitations highlight several avenues for future research. Larger-scale studies across multiple schools and grade levels are needed to evaluate the effectiveness and adaptability of the 31 STEM activities and the 8-step framework in diverse contexts. Cross-cultural comparisons could provide further validation and inform context-specific adaptations. Incorporating quantitative assessments of STEM knowledge, science process skills, and 21st century competencies such as problem-solving, communication, and creativity would allow for stronger claims about cognitive outcomes. Longitudinal designs may also be employed to examine the transfer of skills across disciplines and sustained learning over time.

A promising research direction involves integrating personalized learning systems grounded in self-regulated learning (SRL) theory. SRL emphasizes learners' active role in setting goals, monitoring progress, employing strategies, and reflecting on outcomes (Zimmerman, 2002). Embedding SRL within digital environments could empower students to take ownership of their STEM learning, especially in open-ended, inquiry-based contexts like those featured in this study. Personalized systems, supported by AI or learning analytics, can provide adaptive scaffolds, real-time feedback, and customized learning pathways. For instance, digital dashboards can track student progress through the eight-step STEM framework, prompting reflection, strategy adjustments, or reviews when difficulties arise.

Such systems may also deliver metacognitive prompts to encourage planning and evaluation, particularly important for younger learners with developing executive function (Schumacher and Ifenthaler, 2018). Personalized tools could analyze behavioral patterns, such as engagement duration, revision cycles, or collaboration dynamics, and generate tailored recommendations to support mastery and productivity. Integrating learner profiles that account for prior performance, interests, and preferred strategies would further enhance personalization by adapting task difficulty or VR content to maintain an optimal level of challenge, foster engagement,

and prevent cognitive overload. This approach aligns with personalized self-regulated learning models that position learners as active agents within a system of instructional supports (Romero et al., 2019; Nguyen and Oudeyer, 2018).

Future studies might also investigate how personalized SRL systems influence the development of STEM habits of mind, including perseverance, curiosity, and reflective thinking. By combining immersive STEM activities with adaptive digital support, researchers can design learning environments that are both equitable and effective across diverse learner profiles, advancing the scalability and sustainability of integrated STEM education.

CONCLUSION

This study investigated the perceptions, behaviors, and collaborative patterns of primary students engaged in immersive STEM learning experiences designed around 31 curriculum-aligned activities and supported by VR technologies. The research focused on how such experiences foster interdisciplinary understanding, motivation, and inquiry-based learning, while also examining the behavioral processes through which students engaged in real-world problem-solving. The results revealed that students responded positively to the integrated STEM-VR environment, with a particular emphasis on enjoyment, curiosity, and a deeper conceptual understanding when interacting with immersive technologies. Their reflections demonstrated an evolving appreciation for the interconnectedness of science, technology, engineering, and mathematics, suggesting that interdisciplinary and hands-on learning models can enhance young learners' engagement with STEM subjects. Importantly, analysis of classroom behaviors led to the emergence of an eight-step learning cycle, organically developed by students as they navigated problems, iterated on solutions, and collaborated with peers. This process not only mirrors real-world scientific and engineering practices but also offers a practical pedagogical model for teachers aiming to cultivate inquiry, creativity, and resilience in the classroom. Theoretically, this study contributes to constructivist and self-regulated learning literature by highlighting how immersive tools and open-ended tasks can support student agency, reflection, and cross-disciplinary thinking. Practically, it offers curriculum developers and educators a replicable framework for integrating STEM activities within national science education standards. In summary, this research demonstrates how immersive, inquiry-driven STEM education can transform early science learning from a focus on content delivery to an emphasis on active exploration, laying the groundwork for lifelong scientific literacy, innovation, and critical thinking.

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