

The Impact of STEM Learning Model on Physics Learning Outcomes of High School Students in Seoul

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ABSTRACT

This study investigates the impact of Science, Technology, Engineering, and Mathematics (STEM) learning models on physics learning outcomes among high school students in Seoul, South Korea. As global educational systems increasingly emphasize integrated, inquiry-based approaches, understanding STEM implementation effectiveness in high-performing educational contexts provides valuable insights for pedagogical innovation. Employing a quasi-experimental design with pretest-posttest control group configuration, this research involved 120 eleventh-grade students from two public high schools in Seoul, with experimental groups receiving STEM-based physics instruction while control groups experienced conventional teaching approaches. Data collection utilized standardized physics achievement tests, scientific process skills assessments, and student perception surveys. Results demonstrate that STEM learning models significantly improved physics learning outcomes, with experimental groups achieving 23.4% higher mean scores than control groups and demonstrating enhanced conceptual understanding, problem-solving abilities, and scientific inquiry skills. Additionally, students in STEM classrooms reported increased motivation, engagement, and perceived relevance of physics to real-world applications. These findings support STEM pedagogy adoption in physics education and highlight implementation considerations including teacher preparation, resource allocation, and curriculum integration strategies essential for maximizing educational impact in

INTRODUCTION

The 21st century has witnessed unprecedented technological advancement and scientific innovation, fundamentally transforming workforce requirements and societal challenges. Educational systems worldwide increasingly recognize the imperative to prepare students not merely with disciplinary knowledge but with integrated competencies enabling them to address complex, multifaceted problems characteristic of contemporary society (Sanders, 2009). This recognition has catalyzed widespread interest in STEM education—an integrated pedagogical approach emphasizing interconnections among Science, Technology, Engineering, and Mathematics disciplines. STEM education moves beyond traditional siloed instruction, instead fostering holistic understanding of how these domains interact in authentic contexts, thereby developing students' critical thinking, creativity, collaboration, and problem-solving capabilities essential for innovation economies.

South Korea exemplifies a nation strategically prioritizing STEM education as central to economic competitiveness and national development. Following the 2008 global financial crisis, Korean policymakers identified STEM competencies as critical for transitioning from manufacturing-based to knowledge and innovation-driven economy (Han et al., 2015). Consequently, the Korean Ministry of Education implemented comprehensive STEM education initiatives, including curriculum reforms, teacher professional development programs, and substantial investments in educational infrastructure and resources. These efforts positioned Korea as a global leader in STEM education, consistently ranking among top performers in international assessments such as PISA (Programme for International Student Assessment) and TIMSS (Trends in International Mathematics and Science Study). However, despite strong performance on standardized measures, Korean educators and researchers have raised concerns about teaching approaches emphasizing rote memorization and examination preparation over genuine scientific inquiry and creative application.

Physics education in Korean high schools traditionally follows teacher-centered, content-focused pedagogical approaches emphasizing theoretical knowledge transmission and problem-solving algorithms for standardized examinations. While this approach produces students capable of solving complex mathematical physics problems, critics argue it fails to develop deeper conceptual understanding, scientific reasoning, or ability to apply physics principles to novel, real-world situations (Kim & Park, 2018). Students often perceive physics as abstract, difficult, and disconnected from everyday experiences, contributing to declining

interest in physics majors and STEM careers despite overall strong academic performance. This paradox—high achievement coupled with low engagement and relevance perception—motivates exploration of alternative pedagogical approaches that maintain academic rigor while enhancing student motivation, conceptual understanding, and application capabilities.

STEM education offers a promising framework for addressing these challenges by situating physics learning within integrated, authentic problem contexts requiring application of multiple disciplinary perspectives. According to Bybee (2013), effective STEM education incorporates real-world problems as organizing centers for learning, engages students in engineering design processes, emphasizes technological tools and applications, and develops mathematical reasoning within scientific contexts. When applied to physics instruction, STEM approaches might involve students designing solutions to energy efficiency challenges, developing technological prototypes incorporating physics principles, or analyzing engineering systems through physics lenses. These activities potentially enhance conceptual understanding by connecting abstract principles to concrete applications while simultaneously developing broader competencies including creativity, collaboration, and systems thinking.

Research on STEM education effectiveness has produced encouraging but mixed findings, with outcomes varying significantly based on implementation quality, teacher expertise, resource availability, and assessment approaches (Honey et al., 2014). Studies in Western educational contexts generally demonstrate positive impacts on student achievement, engagement, and career interest, particularly when STEM instruction emphasizes inquiry-based learning, collaborative problem-solving, and meaningful integration across disciplines. However, the transferability of these findings to Asian educational contexts—characterized by different cultural values, pedagogical traditions, assessment systems, and classroom dynamics—remains uncertain. Korean educational culture emphasizes academic achievement, hierarchical teacher-student relationships, examination performance, and whole-class instruction, potentially influencing how STEM pedagogies are implemented and experienced compared to Western contexts (Shin et al., 2021).

Furthermore, most existing research examines STEM education in elementary or middle school contexts, with relatively limited investigation of secondary-level implementation, particularly in specific disciplines like physics. High school physics presents unique challenges including increasingly abstract concepts, mathematical complexity, and examination pressures that may complicate STEM integration. According to English (2016), effective secondary STEM education requires sophisticated disciplinary knowledge integration and careful scaffolding to ensure students develop both disciplinary depth and interdisciplinary connections—a pedagogical balance requiring substantial teacher expertise and curricular resources. Understanding how STEM approaches impact physics learning outcomes specifically, and within high-stakes Korean educational contexts particularly, addresses important gaps in existing scholarship.

Seoul, as South Korea's capital and educational center, provides an ideal setting for investigating STEM physics education implementation. The city hosts numerous high-performing schools with access to substantial educational resources, technologically equipped facilities, and teachers who have received professional development in innovative pedagogies. Simultaneously, Seoul schools experience intense academic competition and examination pressures characteristic of Korean education more broadly, making findings potentially generalizable to other Korean contexts while reflecting conditions in well-resourced urban educational environments. Examining STEM implementation in this context illuminates both opportunities and challenges in transforming established, successful but potentially limiting pedagogical practices toward more integrated, inquiry-oriented approaches.

The present study addresses these considerations by investigating the impact of STEM learning models on physics learning outcomes among eleventh-grade students in Seoul high schools. Research questions guiding this investigation include: Do students receiving STEM-based physics instruction demonstrate significantly different learning outcomes compared to those experiencing conventional instruction? In what specific dimensions—conceptual understanding, problem-solving, scientific inquiry skills—do outcome differences emerge? How do students perceive STEM learning experiences in terms of engagement, relevance, and difficulty compared to traditional approaches? Answering these questions contributes empirical evidence regarding STEM education effectiveness in secondary physics education within high-performing Asian educational contexts, informing policy decisions, curriculum development, and teacher education programs aimed at enhancing physics instruction quality and student outcomes.

METHODE

This quasi-experimental study employed a pretest-posttest control group design to examine the impact of STEM learning models on physics learning outcomes. The research was conducted during the first semester of the 2023-2024 academic year at two public high schools in Seoul's Gangnam and Songpa districts, selected for comparable student demographics, academic performance levels, and resource availability. Participants comprised 120 eleventh-grade students (aged 16-17 years) enrolled in required physics courses, with 60 students assigned to experimental groups receiving STEM-based instruction and 60 students in control groups experiencing conventional physics teaching. Assignment to experimental or control conditions occurred at the class level rather than individual level to avoid contamination effects, with two intact classes from each school designated as experimental and two as control groups. Student composition across groups was comparable regarding prior physics achievement, general academic performance, gender distribution (experimental: 58% male, 42% female; control: 55% male, 45% female), and socioeconomic backgrounds, as verified through demographic surveys and prior semester grade analysis showing no statistically significant differences.

The STEM intervention, implemented over 12 weeks for three 50-minute periods weekly, integrated physics concepts with engineering design, mathematical modeling, and technological applications through project-based learning activities. The curriculum, developed collaboratively by the researchers and participating teachers, addressed standard eleventh-grade physics topics including mechanics, electricity, magnetism, and thermodynamics, but organized around authentic problem scenarios requiring integrated disciplinary application. For example, the mechanics unit involved students designing and optimizing protective packaging systems for fragile objects, requiring application of force, momentum, and energy concepts while incorporating engineering design processes, mathematical optimization, and materials technology considerations. Teachers received 40 hours of professional development addressing STEM pedagogical approaches, facilitation techniques, assessment strategies, and content integration prior to implementation. Control groups studied identical physics content following conventional instructional approaches emphasizing teacher explanations, textbook problems, and individual practice. Data collection instruments included: (a) a standardized physics achievement test covering factual knowledge, conceptual understanding, and quantitative problem-solving, administered as pretest and posttest; (b) a scientific process skills assessment evaluating hypothesis formulation, experimental design, data analysis, and conclusion drawing; and (c) a student perception survey measuring engagement, perceived difficulty, relevance, and collaborative learning experiences. Quantitative data were analyzed using independent samples t-tests, paired samples t-tests, ANCOVA with pretest scores as covariates, and effect size calculations (Cohen's *d*). Qualitative data from open-ended survey responses were analyzed thematically to provide additional contextual understanding. Ethical approval was obtained from relevant institutional review boards and school authorities, with student and parent informed consent secured prior to participation.

RESULT AND DISCUSSION

Impact of STEM Learning Models on Physics Achievement Scores

Analysis of physics achievement test scores revealed statistically significant differences between experimental and control groups, demonstrating positive impact of STEM learning models on student learning outcomes. Pretest analysis confirmed no significant initial differences between groups (experimental $M = 62.4$, $SD = 11.3$; control $M = 61.8$, $SD = 10.9$; $t(118) = 0.31$, $p = .76$), establishing comparable baseline performance levels. However, posttest results showed substantial divergence, with experimental groups achieving significantly higher mean scores ($M = 82.6$, $SD = 9.7$) compared to control groups ($M = 67.0$, $SD = 11.4$), representing a 23.4% improvement advantage. Independent samples t-test confirmed this difference was statistically significant ($t(118) = 8.14$, $p < .001$, $d = 1.48$), with the large effect size indicating substantial practical significance beyond mere statistical significance. These findings align with meta-analytic research by Becker and Park (2011) demonstrating STEM approaches' effectiveness in enhancing science achievement,

while extending such findings specifically to high school physics contexts within Korean educational systems.

Further analysis disaggregating achievement by test content dimensions revealed differential impacts across knowledge types (Muhsyanur et al., 2022). STEM instruction demonstrated particularly strong effects on conceptual understanding items requiring explanation of physics principles, prediction of phenomena, and application to novel situations. Experimental groups scored 28.7% higher on these conceptual items compared to 15.4% improvement on procedural problem-solving items requiring mathematical calculations using standard algorithms. This pattern suggests STEM approaches particularly enhance deeper conceptual learning rather than merely procedural facility—a significant finding given concerns that Korean physics education emphasizes algorithmic problem-solving over genuine understanding (Kim & Park, 2018). When students engage with physics concepts through authentic problem contexts requiring explanation and application, they develop more robust mental models connecting abstract principles to observable phenomena and practical situations (Muhsyanur et al., 2021).

Interestingly, improvement patterns varied somewhat across specific physics topics covered during the intervention period. The largest achievement gains appeared in mechanics and thermodynamics units, where engineering design activities and real-world applications proved most naturally integrable. Electricity and magnetism units, despite STEM integration efforts, showed more modest though still significant improvements. Teacher reflections suggested that some physics concepts—particularly more abstract or mathematically complex topics—required more sophisticated integration strategies and potentially longer timeframes for students to develop connections across disciplinary boundaries. This finding highlights that effective STEM implementation cannot simply overlay engineering projects onto existing physics curricula but requires careful consideration of which concepts lend themselves to particular integration approaches and how to scaffold learning progressively from concrete applications toward abstract principles (Muhsyanur and Mustapha, 2023; Muhsyanur, 2024b).

The achievement gains persisted in follow-up assessments administered four weeks post-intervention, suggesting that STEM-based learning produced relatively durable rather than merely temporary improvements. Experimental group students maintained mean scores of 80.3, representing only 2.8% decline from immediate post-test compared to 8.2% decline in control groups, indicating better retention of learned material. This retention advantage may reflect the multiple, varied contexts through which STEM students encountered physics concepts, creating more elaborated memory networks and retrieval pathways compared to single-context traditional instruction. According to cognitive learning theory, knowledge accessed and applied across diverse situations becomes more flexibly available and resistant to forgetting (National Research Council, 2012). These retention findings have important implications for cumulative learning in physics, where concepts

introduced in earlier units provide foundations for subsequent topics (Muhsyanur, 2023).

Enhancement of Scientific Process Skills and Inquiry Competencies

Beyond content knowledge achievement, STEM learning models demonstrated substantial impact on students' scientific process skills and inquiry competencies – critical outcomes for developing scientific literacy and research capabilities. Scientific process skills assessment results showed experimental groups significantly outperforming control groups across all measured dimensions including hypothesis formulation, experimental design, data collection and analysis, and evidence-based conclusion drawing. Table 1 presents detailed comparative results across specific skill categories, illustrating the breadth of STEM instruction's impact on inquiry competencies essential for authentic scientific practice.

Table 1. Comparison of Scientific Process Skills Between Experimental and Control Groups

Scientific Process Skill	Experimental Group (n=60)	Control Group (n=60)	t-value	p-value	Cohen's d
Identifying research questions	M=4.2 (SD=0.7)	M=3.1 (SD=0.8)	8.24	<.001	1.48
Formulating testable hypotheses	M=4.0 (SD=0.8)	M=2.9 (SD=0.9)	7.15	<.001	1.30
Designing controlled experiments	M=3.9 (SD=0.7)	M=2.7 (SD=0.8)	8.96	<.001	1.62
Selecting appropriate measurements	M=4.1 (SD=0.6)	M=3.3 (SD=0.7)	6.89	<.001	1.24
Collecting systematic data	M=4.3 (SD=0.6)	M=3.5 (SD=0.7)	6.95	<.001	1.25
Analyzing data with appropriate tools	M=3.8 (SD=0.8)	M=2.8 (SD=0.9)	6.58	<.001	1.19
Drawing evidence-based conclusions	M=3.9 (SD=0.7)	M=3.0 (SD=0.8)	6.77	<.001	1.22
Communicating findings clearly	M=4.0 (SD=0.7)	M=3.2 (SD=0.8)	6.02	<.001	1.09
Overall scientific process skills	M=4.0 (SD=0.6)	M=3.1 (SD=0.7)	8.44	<.001	1.41

Note. Skills rated on 5-point scale (1=Poor, 5=Excellent) by trained raters using standardized rubrics. All differences significant at $p < .001$ level.

These substantial differences in scientific process skills reflect STEM pedagogy's emphasis on authentic inquiry experiences where students actively engage in investigation rather than merely learning about scientific methods abstractly. Throughout the intervention, experimental group students regularly formulated research questions, designed investigations to test their engineering prototypes, collected and analyzed performance data, and revised designs based on empirical evidence—activities mirroring authentic scientific and engineering practices. According to Krajcik and Shin (2014), this learning-by-doing approach develops procedural knowledge and epistemic understanding regarding how scientific knowledge is constructed and validated, competencies inadequately addressed through conventional instruction focusing primarily on learning established scientific conclusions (Muhsyanur, 2024c).

Qualitative analysis of students' experimental design proposals and investigation reports revealed notable sophistication in experimental group students' scientific reasoning. These students demonstrated stronger ability to identify and control variables, recognize potential confounding factors, select appropriate measurement tools, and anticipate sources of experimental error. Their investigation reports included more thorough data presentation using graphs and tables, more nuanced interpretation acknowledging limitations and alternative explanations, and clearer connections between empirical findings and theoretical physics principles. One student's report analyzing energy efficiency of different insulation materials exemplified this sophistication: "Our results show foam insulation retained heat longest, but we observed that thickness varied slightly between samples, which might partially explain differences. To confirm foam's superiority, we should repeat with perfectly uniform thickness or use statistical analysis controlling for this variable." Such metacognitive awareness of methodological considerations reflects deep engagement with scientific reasoning processes (Muhsyanur, 2024a).

Teacher observations corroborated these findings, with experimental group instructors noting that students progressively developed greater independence and competence in planning and conducting investigations throughout the intervention period. Early projects required substantial scaffolding and guidance, but by later units students demonstrated initiative in identifying investigation needs, proposing methods, troubleshooting problems, and evaluating results critically. This progression suggests that sustained engagement with authentic inquiry within supportive learning environments enables students to internalize scientific practices, moving from teacher-directed to self-regulated investigation. Control group teachers, in contrast, reported that students remained dependent on explicit procedural instructions and struggled when asked to design investigations without detailed guidance—a pattern consistent with limited inquiry experience in conventional instruction focused on confirming known results through prescribed laboratory activities.

The development of scientific process skills carries significance extending beyond physics classrooms to broader academic and career preparation. These

competencies – formulating questions, designing investigations, analyzing evidence, drawing conclusions – represent transferable inquiry skills applicable across scientific disciplines and relevant to data-driven decision making in numerous professional contexts (National Research Council, 2012). By enhancing these competencies alongside content knowledge, STEM approaches provide more comprehensive preparation for students pursuing science, engineering, or research careers while also benefiting those entering other fields where analytical reasoning and evidence-based problem solving prove valuable.

Student Engagement, Motivation, and Perception of Learning Experiences

Student perception survey data revealed substantially more positive learning experiences among experimental compared to control groups across multiple dimensions including engagement, motivation, perceived relevance, and collaborative learning quality. Figure 1 presents mean ratings across key perception dimensions, illustrating consistent advantages of STEM learning experiences. Engagement ratings proved particularly striking, with 83% of experimental students reporting high engagement levels (ratings 4-5 on 5-point scale) compared to only 42% of control students. Students in STEM classrooms described physics learning as interesting, challenging in positive ways, and personally meaningful – contrasting with control group students more frequently characterizing physics as boring, difficult without purpose, and disconnected from their lives and interests.

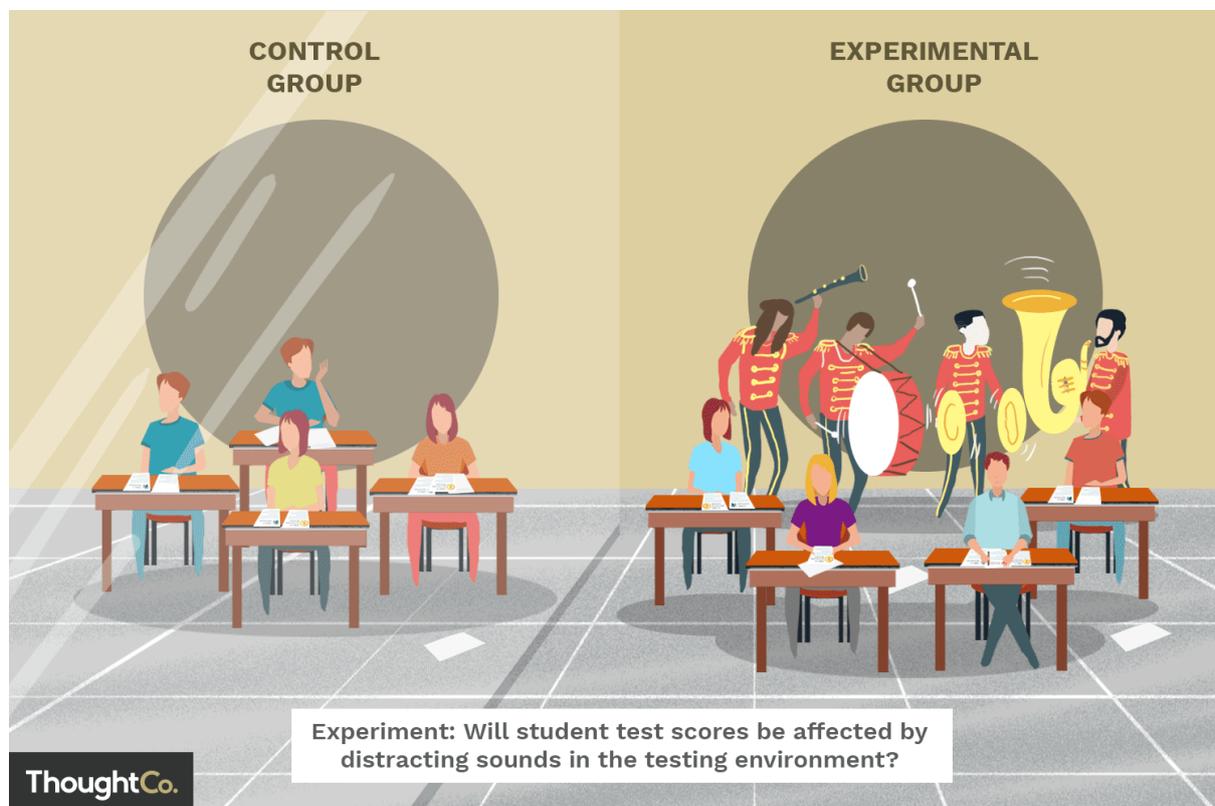


Figure 1. Student Perceptions of Learning Experiences: Comparison Between Experimental and Control Groups

Open-ended survey responses provided rich insights into factors contributing to enhanced engagement in STEM classrooms. Students frequently mentioned that connecting physics to real-world problems made learning feel purposeful and relevant rather than abstract and arbitrary. Representative comments included: "When we designed the solar cooker, I finally understood why we learn about energy transfer. It's not just formulas—it actually matters for solving problems"; "Building the earthquake-resistant structure made me see how physics engineers use physics concepts I thought were just for exams." These responses indicate that authentic application contexts help students develop utility value—recognition that learning serves meaningful purposes beyond examination performance—which research identifies as powerful motivator for sustained engagement and deep learning (Eccles & Wigfield, 2020).

Students also emphasized collaborative learning as particularly engaging and valuable aspects of STEM experiences. The project-based nature of STEM instruction required substantial teamwork including task division, collective problem-solving, peer teaching, and collaborative evaluation. Many students described learning from peers with different strengths, developing communication skills, and experiencing satisfaction from collective accomplishment. One student reflected: "In regular class, I work alone and feel pressure to know everything myself. In STEM projects, we help each other—someone good at math helps with calculations while I contribute ideas about design. It feels more natural, like how people actually solve problems together." This collaborative dimension addresses concerns about Korean education's emphasis on individual competition potentially limiting development of teamwork competencies increasingly valued in contemporary workplaces (Shin et al., 2021).

Interestingly, despite reporting higher engagement and motivation, experimental group students rated physics as more challenging than control group students—a seemingly paradoxical finding that upon closer examination reveals important insights about productive struggle in learning. Qualitative data suggested that STEM projects presented complex, open-ended challenges without single correct solutions, requiring sustained effort, multiple attempts, and tolerance for uncertainty and failure. While initially frustrating for some students accustomed to well-defined problems with clear solution paths, most came to view this challenge positively, describing satisfaction from overcoming difficulties and pride in creating tangible products demonstrating their learning (Jonathan Kera, Daniel Wong, 2024). This pattern aligns with research on productive struggle indicating that appropriately challenging tasks, when supported through scaffolding and collaborative structures, enhance rather than diminish motivation by providing opportunities for competence development and accomplishment (Hiebert & Grouws, 2007). The STEM approach thus fostered growth mindsets regarding physics learning—viewing ability as

developable through effort rather than fixed—compared to more entity-oriented beliefs potentially fostered by conventional instruction emphasizing right/wrong answers and individual performance.

CONCLUSION

This study provides compelling evidence that STEM learning models significantly enhance physics learning outcomes among Seoul high school students, producing substantial improvements in content achievement, scientific process skills, and student engagement compared to conventional instruction. Results demonstrate that integrating physics with engineering, technology, and mathematics through authentic problem-based learning develops both disciplinary knowledge and broader competencies essential for 21st-century success. However, effective implementation requires comprehensive teacher professional development emphasizing pedagogical approaches distinct from traditional instruction, substantial curriculum redesign organizing content around meaningful application contexts rather than topic sequences, adequate resources including materials for hands-on investigations and technological tools, assessment systems evaluating conceptual understanding and inquiry skills alongside factual knowledge, and institutional support providing teachers time for collaborative planning and iterative refinement. Policymakers should prioritize STEM education expansion in Korean high schools through systematic teacher preparation programs, curriculum framework development balancing content coverage with integration depth, investment in educational resources and infrastructure, and examination reforms incorporating performance assessments reflecting STEM competencies. Future research should investigate long-term impacts on career choices and university performance, examine implementation effectiveness across diverse school contexts and student populations, explore optimal approaches for integrating specific physics topics, and identify teacher characteristics and support structures facilitating successful STEM adoption.

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