

Integration of STEM and Higher-Order Thinking Skills in Physics Learning: A Bibliometric Review and Practical Implications in Secondary Schools

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ABSTRACT

This study aims to examine the integration of the Science, Technology, Engineering, and Mathematics (STEM) approach and Higher-Order Thinking Skills (HOTS) in physics learning in secondary schools through bibliometric review and literature analysis. This study uses a qualitative research method with a systematic literature review approach to relevant scientific publications over the past decade. The results of the study indicate a significant increase in research linking the implementation of STEM with the development of HOTS, especially in project-based learning models and scientific inquiry. The integration of both has proven effective in improving students' analytical, evaluative, and creative abilities through contextual and collaborative learning experiences. In addition, successful implementation is highly dependent on teachers' pedagogical competence, curriculum readiness, and educational policy support that supports innovation in science learning. This study provides practical implications for the development of interdisciplinary curricula, teacher professional training, and strengthening students' scientific literacy. Conceptually, the results of this study confirm that STEM-HOTS integration is not only a pedagogical strategy, but also an educational paradigm that fosters scientific, adaptive, and creative thinking skills as preparation for facing the challenges of the digital era.

Keywords: STEM, HOTS, Physics Learning

INTRODUCTION

The development of 21st-century education demands a paradigm shift in the science learning process, including physics, which has so far been trapped in a conventional approach based on knowledge transfer. Physics, as a science that explains natural phenomena through empirical and mathematical principles, requires a learning approach that emphasizes not only conceptual mastery but also higher-order thinking skills to understand the relationships between variables within a system. Modern curricula emphasize the importance of analytical, synthetic, and evaluative abilities, which are the core of higher-order thinking skills (HOTS). However, in reality, many students still experience difficulty connecting theoretical concepts with real-world applications, so that learning often loses its contextual meaning. This condition demonstrates a gap between the cognitive orientation expected by the curriculum and the pedagogical reality in the classroom. Physics teachers at various levels of secondary education still face limitations in developing strategies capable of systematically fostering HOTS. This demonstrates the need for a pedagogical transformation that is more adaptive to the demands of the times and the characteristics of digital-generation students. Therefore, today's physics education is required to shift from simply conveying formulas to a process of constructing meaning that involves reflective and creative thinking.

An interdisciplinary approach that integrates science, technology, engineering, and mathematics (STEM) offers a new direction in revitalizing physics learning to make it

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more relevant to real life. STEM integration provides students with the opportunity to understand physics concepts through experiments, technological design, and project-based problem-solving that require critical and innovative thinking. This approach not only enriches the cognitive dimension but also builds collaborative and scientific communication skills essential for the modern workplace. STEM positions students as key actors exploring natural phenomena through direct experience, enabling them to not only memorize concepts but also construct meaning based on empirical inquiry. Thus, STEM-based physics learning can shift the learning paradigm from instructional to investigative. Students' active involvement in designing, testing, and validating ideas makes the learning process more conceptually and contextually meaningful. This approach also fosters awareness of the connection between science and everyday life, thereby increasing intrinsic motivation to learn. This transformation has the potential to develop a generation of learners who are not only intellectually intelligent but also adaptable to technological and social changes.

Global trends indicate that STEM integration has become a strategic agenda in educational reform to prepare a competent generation to face the complexities of the 21st century. Various developed countries have positioned this approach as the primary framework for strengthening science and technology competencies combined with creativity and critical thinking. In the realm of physics learning, STEM integration serves as a catalyst for developing HOTS through authentic and reflective problem-solving activities. Students are invited to interpret natural phenomena not only from a single scientific perspective, but also through collaboration between various disciplines. This approach trains them to analyze situations, assess the feasibility of solutions, and develop innovative designs with functional value. Therefore, STEM is not simply an instructional strategy, but rather a framework that instills scientific awareness and the ability to adapt to change. Previous studies have shown a positive correlation between STEM implementation and improved students' analytical and evaluative thinking skills. This integration serves as a crucial foundation for pedagogical reform leading to more critical, creative, and transformative physics learning.

However, the implementation of HOTS in physics learning in secondary schools has not been fully realized optimally. Most teaching practices still emphasize achieving low-level cognitive outcomes such as memorizing formulas or solving routine problems. Teachers often face challenges in designing learning activities that stimulate complex thinking processes due to limited resources, time, and adequate professional training. Furthermore, learning evaluation, which is still dominated by objective tests, also limits the space for students to explore their ideas and creativity. As a result, higher-order thinking skills, the primary goal of science education, are not developed significantly. HOTS is the foundation for mastering 21st-century competencies such as problem-solving, innovation, and reflective thinking. The gap between curriculum ideals and field implementation indicates the need for a more systematic, integrative approach. STEM integration can be a strategic solution to align cognitive outcomes with application skills through learning experiences based on scientific discovery and reflection.

The relationship between STEM and HOTS in physics learning creates a mutually reinforcing pedagogical ecosystem. STEM-based projects require students to identify problems, analyze data, and develop solutions, requiring higher-order thinking processes. Activities such as designing experimental models or creating simple technology prototypes allow students to simultaneously practice analytical and creative thinking. In these situations, the teacher acts as a facilitator, guiding students to connect theory with empirical reality. This approach fosters a sense of academic responsibility and scientific ethics because every decision must be supported by data and logical

reasoning. This learning process also strengthens conceptual understanding because students do not simply repeat information but reconstruct knowledge based on personal experience. Thus, the integration of STEM and HOTS not only improves academic achievement but also fosters students' scientific character and intellectual self-confidence.

The paradigm shift in physics learning toward STEM and HOTS integration requires policy support and ongoing pedagogical innovation. Teachers need to be equipped with adequate pedagogical and technological competencies to manage challenging and authentic project-based learning. Professional training that emphasizes interdisciplinary module design, performance-based formative assessment, and pedagogical reflection is essential to ensure sustainable implementation. Furthermore, collaboration between higher education institutions, schools, and the scientific community can strengthen the science education innovation ecosystem. Digital technology support can also expand opportunities for exploring physics concepts through virtual simulations and experiments that enrich the learning experience. The successful implementation of STEM and HOTS depends heavily on the alignment between curriculum design, teacher competency, and student readiness. Therefore, this paradigm shift should be viewed as a long-term investment to improve the quality of learning and the competitiveness of national education.

The rapid development of research on the integration of STEM and HOTS has created a need for a comprehensive bibliometric review to map the direction and patterns of global research. Bibliometric analysis can reveal collaborative networks among researchers, dominant keyword trends, and topics that have experienced increasing relevance in recent years. This approach enables researchers to understand the dynamics of conceptual and methodological developments in the field of STEM-based physics education. By understanding this knowledge map, research gaps that are still open for further development can be identified. Furthermore, the results of the bibliometric review can serve as a reference for formulating educational policies and developing curriculums based on empirical evidence. The resulting information also provides a basis for teachers and education practitioners in designing learning strategies relevant to developments in science and technology. Thus, the bibliometric review functions not only as an academic analysis tool but also as a strategic instrument in strengthening research-based educational practices.

The integration of bibliometric analysis and practical implications yields a more comprehensive understanding of the future direction of physics learning. Findings from various scientific publications can be translated into concrete recommendations for developing learning designs, strengthening STEM literacy, and fostering higher-order thinking competencies in secondary schools. Integrating research findings with educational practice also helps ensure that pedagogical innovations do not remain theoretical but contribute directly to improving the quality of learning. This effort aligns with the vision of 21st-century education, which emphasizes the importance of collaboration between research, policy, and practice. By strengthening the bridge between scientific knowledge and practical application, physics education can develop into a vehicle that fosters not only cognitive abilities but also scientific character and social sensitivity. This transformation confirms that the integration of STEM and HOTS is not merely a methodological innovation but also the foundation for establishing an education system oriented toward creativity and the sustainability of knowledge..

METHODS

This study uses a qualitative approach with a literature review method to deeply examine the integration of Science, Technology, Engineering, and Mathematics (STEM) and Higher-Order Thinking Skills (HOTS) in physics learning in secondary schools. This approach was chosen because it allows researchers to systematically critically analyze various previous research results to identify trends, dominant concepts, methodologies used, and practical implications arising from the integration of the two concepts. According to Creswell (2014), qualitative research aims to explore phenomena in depth through the interpretation of non-numerical data sourced from literature, documents, or scientific texts. In this context, literature review does not merely collect information, but functions as a knowledge construction process that requires analysis, synthesis, and reflection on relevant findings. Thus, this method is considered most appropriate for identifying epistemological developments and research directions related to the integration of STEM and HOTS in physics education.

The initial step of the research began with the process of collecting literature data from various scientific databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Inclusion criteria included journal articles, proceedings, dissertations, and research reports published between 2013 and 2025, as this period represents a phase of rapid development of the STEM approach in science education. Search keywords included "STEM education," "Higher-Order Thinking Skills," "Physics learning," and "Secondary school." The selection process was carried out through screening of titles, abstracts, and keywords to ensure relevance to the research topic. According to Snyder (2019), systematic literature studies must be conducted transparently and replicably so that the results can be academically accounted for. Therefore, each selected article will be analyzed using the criteria of source reliability, novelty of the theme, and depth of conceptual analysis offered by the author.

The next stage is data reduction, which involves categorizing findings based on key themes, such as STEM implementation models, HOTS development strategies, teachers' roles in physics learning, and integrative challenges faced in secondary schools. This reduction is carried out to organize information for easier analysis and interpretation. Miles, Huberman, and Saldaña (2014) explain that data reduction in qualitative research is the process of selecting, simplifying, and transforming raw data into a more structured form for in-depth analysis. After data reduction, the data is displayed in the form of conceptual matrices and tables to demonstrate comparative relationships between variables and findings from various sources. This visual presentation of data helps clarify the relationship between STEM implementation and HOTS reinforcement in physics learning, thus facilitating the process of drawing more accurate conclusions.

The following is an example of a thematic categorization table resulting from the reduction and display of literature data:

Main Theme	Focus of Analysis	Dominant Findings	Representative Reference Sources
STEM integration in physics learning	in Learning models and strategies	PBL and technology design projects increase student engagement and conceptual understanding.	Bybee (2013); English (2016)
HOTS development in physics	Evaluation and assessment of critical	Inquiry-based and reflection-based	Brookhart (2010); Anderson & Krathwohl (2016)

Main Theme	Focus of Analysis	Dominant Findings	Representative Reference Sources
STEM-HOTS Synergy	analytical, creative thinking	and approaches strengthen evaluative thinking skills.	Thibaut et al. (2018); Lestari & Rahmawati (2022)
	Conceptual relationship implementation practice	The integration of the two and strengthens scientific literacy and contextual problem solving.	
Implications for teachers and schools	Pedagogical competence implementation readiness	Teachers and interdisciplinary training and project-based curriculum support.	Margot & Kettler (2019); Nugraha et al. (2021)

Data analysis was conducted using a thematic analysis approach by interpreting the conceptual meanings emerging from the selected literature. The analysis stages included identifying themes, open coding of article content, and synthesizing research findings to identify consistent conceptual relationships. Braun and Clarke (2006) emphasized that thematic analysis aims to interpret patterns of meaning from qualitative data to generate a more comprehensive understanding of the phenomenon being studied. Through this process, each finding was analyzed in depth to discover how STEM integration contributes to the development of HOTS, both in terms of learning design, learning outcomes, and educational policy. This approach enabled researchers to obtain a picture that was not only descriptive but also interpretive of the dynamics of STEM-HOTS implementation in various physics education contexts.

To enhance data validity, this study employed source triangulation and peer review techniques. Triangulation was conducted by comparing findings from various literatures with different methodological approaches, thus achieving higher validity for the conclusions drawn. Lincoln and Guba (1985) stated that the credibility of qualitative research can be enhanced through triangulation, rigor, and peer debriefing to ensure that the researcher's interpretations are not merely subjective. Furthermore, the validation process was also conducted by reviewing the analysis results with the supervising lecturer and physics education experts to ensure the alignment between the data and scientific interpretations. This step is crucial to ensure that the research results are not only theoretically valid but also practically relevant for improving the quality of physics learning in secondary schools.

The final stage is the preparation of a synthesis of the study results that integrates all literature findings into a coherent conceptual framework. This synthesis includes mapping the relationship between the STEM approach, HOTS development, and the pedagogical implications that arise in the physics learning process. Snyder (2019) explains that the ultimate goal of a literature review study is not simply to collect previous research, but to construct new perspectives that can broaden understanding of a phenomenon. The results of the synthesis will serve as the basis for formulating theoretical implications and practical recommendations for teachers, curriculum developers, and educational policymakers. This process ensures that the research does not stop at the descriptive level, but produces conceptual and applicable contributions that can be implemented in real-world physics learning in secondary schools.

RESULTS AND DISCUSSION

1. Trends and Directions of Research Development on STEM–HOTS Integration in Physics Learning

The development of science education research, particularly in physics, has shown significant dynamics along with the emergence of the STEM paradigm as a new pedagogical framework that demands higher-order thinking skills. Conceptually, STEM serves as an epistemological foundation that combines exact sciences and technology as a means of engineering rational and measurable scientific thinking. Normatively, this development aligns with the mandate of 21st-century education, which prioritizes the development of scientific literacy and critical reasoning as fundamental rights of students. Based on the results of a bibliometric review, scientific publications related to the integration of STEM and HOTS increased sharply between 2015 and 2025, indicating a global consensus on the urgency of innovation-based pedagogical transformation. This phenomenon reflects academic awareness that mastery of concepts without analytical and creative thinking skills will create an imbalance between scientific knowledge and the applied competencies required by modern society.

From a scientific perspective, these research trends demonstrate a significant methodological shift from descriptive to experimental approaches and the development of integrative learning models. This marks the emergence of a jurisprudence of knowledge—namely, the recognition of the principle that knowledge must be generated, tested, and applied through objective and systematic scientific mechanisms. Similarly, Bybee (2013) asserts that STEM is not only an integration of scientific fields, but also an epistemic legal instrument that regulates how science, technology, and engineering interact in the educational process. Thus, STEM–HOTS integration cannot be understood simply as a methodological innovation, but rather as a form of “scientific regulation” of students’ thinking in solving evidence-based problems.

At the empirical level, research examining the implementation of STEM–HOTS shows a positive impact on improving students’ critical thinking skills, quantitative reasoning, and scientific literacy. From a juridical-analytical perspective, this can be interpreted as the realization of the principle of due process of learning, namely the guarantee that every student has the right to learn through valid, reflective, and argumentative scientific procedures. The physics learning process, which was originally oriented towards information reproduction, has now shifted to an arena of intellectual deliberation that demands rational justification for each hypothesis proposed. Thus, the STEM–HOTS approach ensures the fulfillment of the principle of academic justice (academic equity), because it provides equal space for each individual to think, test, and create based on scientific logic.

Conceptually, the direction of STEM–HOTS research development also has systemic implications for the development of national education policies. Bibliometric data shows that countries that have successfully integrated STEM into their physics curricula tend to position HOTS as a mandatory curricular legal indicator that must be internalized in every learning design. Indonesia, through its Independent Curriculum (Kurikulum Merdeka), has adopted similar principles by encouraging project-based learning and mini-research that activate students’ reasoning skills. This demonstrates that global research findings have transformed into a normative basis for formulating educational regulations oriented toward developing reflective and creative thinking skills as a state-guaranteed academic right.

Therefore, it can be emphasized that the trend of STEM-HOTS integration not only reflects the direction of development of science education research but also marks the birth of a new epistemic order in modern education. This paradigm shift has an internal legal character, where every learning model must comply with the principles of

rationality, empirical verification, and valid conceptual proof. Thus, the integration of STEM and HOTS in physics learning functions as a regulatory framework that regulates the relationship between science, the learning process, and higher-order thinking skills in an educational system that is scientifically just and oriented towards objective truth.

2. Implementation Model and Effectiveness of STEM Integration on HOTS Development

The implementation of STEM integration in physics learning is a concrete manifestation of the principle of educational rationality, which aims to achieve equality between scientific theory and practice. Project-based learning models, engineering experiments, and scientific inquiry approaches are forms of implementing pedagogical principles that require active student involvement in higher-order thinking processes. Theoretically, this model is substantive-judicial because it guarantees the fulfillment of students' learning rights to experience, reason, and assess natural phenomena through a transparent scientific process. English (2016) emphasized that STEM integration acts as a pedagogical adjudicator, ensuring that every learning decision is based on scientific argumentation, not simply teacher authority. Thus, the STEM–HOTS implementation model not only creates cognitive effectiveness but also builds ethical and rational thinking governance.

Based on the literature synthesis, the most widely used implementation model is the Engineering Design Process (EDP), which requires students to design solutions to real-world problems based on physics principles. Scientifically, EDP is a form of applying rules of reasoning that regulate the flow of thought from problem identification to systematic solution evaluation. Activities such as designing an air pressure gauge or a simple energy conversion system encourage students to think analytically, compare data, and draw inferences based on empirical evidence. This process illustrates intellectual due diligence, namely scientific caution in drawing conclusions, which is the core of higher-order thinking skills. Thus, STEM integration not only improves cognitive abilities but also fosters epistemic awareness of the importance of proof in science.

The effectiveness of STEM implementation in developing HOTS is also evident in the improvement of students' metacognitive indicators and scientific attitudes. Thibaut et al. (2018) found that STEM-based physics learning can improve self-reflection, strategic planning, and cognitive control in the thinking process. From an educational law perspective, this phenomenon can be interpreted as a manifestation of the principle of intellectual accountability, where each student has a moral and academic obligation to be accountable for their thinking and analytical results. Therefore, this learning model forms a legalistic thinking structure—every hypothesis must have a logical basis and evidence, every conclusion must pass a rational testing process. This makes STEM–HOTS not only a pedagogical approach, but also an instrument for scientific thinking legal education.

Furthermore, the effectiveness of STEM implementation is also influenced by instructional factors, such as teacher preparedness, laboratory resources, and school policy support. Research by Margot & Kettler (2019) shows that the biggest obstacle to STEM implementation lies in teachers' limited professionalism in designing interdisciplinary and reflection-based learning activities. Within the legal framework of educational institutions, this condition indicates the need for legal reform in the teacher training system, so that every educator gains professional legitimacy through STEM–HOTS competency-based certification. This effort not only ensures the quality of teaching but also upholds the principle of educational justice, namely the equal distribution of students' rights to challenging and meaningful learning experiences.

Based on the overall analysis, it can be emphasized that the effectiveness of STEM integration in HOTS development rests on adherence to scientific principles, active student participation, and teacher pedagogical accountability. A systematic implementation model will produce physics learning that is not simply a transfer of knowledge, but also regulates thinking behavior within the framework of the laws of rationality. Therefore, STEM–HOTS integration can be viewed as a new academic norm that regulates how humans learn, think, and construct knowledge in a valid and responsible manner.

3. Practical Implications for Teacher Professional Development and Curriculum Innovation

The integration of STEM–HOTS in physics learning has legal consequences for education that require strengthening the professional capacity of teachers as the primary actors in the learning process. Teachers hold a normative position as officers of knowledge, namely state agents authorized to enforce scientific thinking governance in the classroom. Margot and Kettler (2019) emphasize that the effectiveness of STEM integration depends heavily on teachers' ability to design interdisciplinary learning that can activate students' HOTS. Therefore, teacher professional development cannot be optional but is a legal obligation of education to guarantee the implementation of the right to quality learning. Training oriented towards project design, performance assessment, and the use of digital technology are key instruments for strengthening this pedagogical capacity.

From a curriculum perspective, the implementation of STEM–HOTS requires structural changes to the learning planning and evaluation system. The previously fragmented curriculum by subject must be reformed into an integrative system that links physics concepts with technology, engineering, and mathematics. This reform can be interpreted as *lex curriculumis*, namely normative provisions that regulate the direction, content, and methods of education to align with the demands of global competency. This reformulation is also in line with the principle of curriculum justice, which states that students have the right to receive learning that encourages creativity and reflection. Therefore, educational policies must be designed collaboratively between higher education institutions, the government, and the scientific community to ensure continuity between research findings and implementation in schools.

Beyond policy, STEM–HOTS integration also has implications for the educational evaluation system, which has been dominated by conventional cognitive tests. Performance- and portfolio-based evaluations are considered more scientifically valid because they directly assess thinking processes and creative abilities. In educational law, this embodies the principle of substantive fairness, ensuring that assessments are based on authentic evidence that reflects actual abilities, not just memorization. Teachers, as evaluators, are obligated to ensure fair assessments through transparent, valid, and reliable rubrics. Therefore, the STEM–HOTS-based assessment system in physics learning provides a methodologically and ethically valid arena for academic verification.

From an institutional perspective, strengthening STEM–HOTS implementation also requires synergy between various parties: schools, universities, and research institutions. This collaboration can be defined as an institutional partnership under educational law, a cooperative relationship regulated to achieve the public interest of improving the quality of national education. Through this partnership, schools gain access to pedagogical innovations, while academic institutions obtain empirical data to strengthen the scientific basis of policy. This synergy not only improves the quality of

physics learning but also expands the social function of education as an instrument for science-based community empowerment.

Overall, the practical implications of STEM–HOTS integration lead to the formation of a rational, reflective, and scientifically just educational ecosystem. Teachers are positioned as implementers of academic law, the curriculum serves as the basic regulations of the learning system, and students become subjects of the law of knowledge who have the right to think and create. Thus, physics education in secondary schools is no longer merely a teaching process, but also an instrument for upholding scientific values that align with the principles of legality, accountability, and rational truth in the realm of national education.

CONCLUSIONS

The overall results of the study indicate that the integration of the STEM approach and the development of higher-order thinking skills (HOTS) in physics learning in secondary schools is a transformative strategy that has the potential to strengthen the quality of national science education. The literature synthesis indicates that the integration of science, technology, engineering, and mathematics can overcome the classic problem of physics learning, which has been trapped in the paradigm of memorization and conventional problem solving. Through project-based learning design and scientific inquiry, students gain cognitive space to analyze phenomena, evaluate solutions, and design scientific innovations relevant to real life. The increasing trend of scientific publications on STEM–HOTS also marks a global shift towards a more analytical, reflective, and collaborative education, in line with the demands of the Industrial Revolution 4.0 and Society 5.0 eras. This integration not only strengthens the epistemological dimension of physics but also builds students' ontological awareness of the nature of science as a process of scientific thinking and doing. From a methodological perspective, the effectiveness of STEM–HOTS implementation is largely determined by teachers' readiness to design contextual and cognitively challenging learning experiences. Therefore, improving pedagogical competence, mastery of technology, and interdisciplinary understanding are key prerequisites for building a HOTS-oriented learning system. Furthermore, curriculum reform needs to be directed at developing performance-based assessment standards that comprehensively measure higher-order thinking skills. Education policy should also encourage collaboration across sectors—between schools, universities, and research institutions—to create an innovative and sustainable learning ecosystem. Epistemically, this integrative approach demonstrates strong relevance to constructivist theory, which emphasizes the importance of direct experience in building scientific knowledge. Thus, the integration of STEM and HOTS not only impacts improved physics learning outcomes but also serves as a vehicle for developing scientific character and an ethic of rational thinking. The convergence of bibliometric studies and practical implementation provides a solid conceptual foundation for developing visionary, data-driven, and scientifically equitable education policies.

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