

Integrating Stem Education to Foster Critical Thinking, Collaboration, Communication, and Creativity in Science Education

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Abstract

STEM education, which integrates Science, Technology, Engineering, and Mathematics, has emerged as an effective instructional approach for improving science education and equipping learners with the competencies required for the twenty-first century. This paper examines how the integration of STEM education fosters critical thinking, collaboration, communication, and creativity through inquiry-based learning, project-based learning, engineering design, technology integration, and authentic problem-solving. It discusses the concepts of STEM education and the four core competencies, highlighting their relevance to science teaching and learning. The paper further explores strategies for integrating STEM into science education, its benefits, challenges, implications for teaching and learning, and recommendations for effective implementation. It concludes that integrating STEM education into science classrooms enhances scientific literacy, innovation, problem-solving, and lifelong learning, thereby preparing learners to address contemporary scientific, technological, environmental, and societal challenges while contributing to sustainable national development.

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Introduction

The rapid advancement of science, technology, and innovation has significantly transformed the knowledge, competencies, and skills required for success in today's society. The increasing complexity of global challenges such as climate change, environmental sustainability, artificial intelligence, digital transformation, healthcare improvement, and economic development requires individuals who possess not only subject knowledge but also the ability to think critically, communicate effectively, collaborate with others, and develop creative solutions to emerging problems (Organisation for Economic Co-operation and Development [OECD], 2019). Consequently, educational systems worldwide are shifting from traditional teacher-centred approaches toward learner-centred pedagogies that prepare students for the demands of the twenty-first century.

Science education occupies a central position in this transformation because it equips learners with scientific knowledge, inquiry skills, and problem-solving abilities that enable them to understand natural phenomena and address real-world challenges. Modern science education extends beyond the transmission of scientific facts to emphasise scientific literacy, innovation, technological competence, and the application of knowledge to everyday life. To achieve these goals, science education increasingly adopts interdisciplinary instructional approaches that integrate scientific concepts with technology, engineering, and mathematics, thereby preparing learners for the knowledge-based economy and sustainable development (UNESCO, 2021).

Among these educational innovations, STEM education has gained considerable recognition as an effective instructional approach for developing learners who are scientifically literate, technologically competent, innovative, and capable of solving real-world problems. STEM is an acronym for Science, Technology, Engineering, and Mathematics, representing an interdisciplinary educational approach that integrates concepts and practices from these four disciplines into meaningful learning experiences rather than teaching them as

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isolated subjects (Ortiz-Revilla, Greca, and Arriasecq, 2021). Through this integration, science education becomes more practical, inquiry-driven, and relevant to learners by connecting scientific theories with technological applications, engineering design, and mathematical reasoning.

Conceptually, STEM education emphasises the application of knowledge to authentic situations through inquiry, experimentation, engineering design, and mathematical reasoning. It encourages students to ask scientific questions, investigate problems, develop hypotheses, collect and analyse evidence, design innovative solutions, test prototypes, and refine their ideas based on evidence. According to Ortiz-Revilla et al. (2021), integrated STEM education provides learners with opportunities to connect disciplinary knowledge while developing competencies required for scientific inquiry, innovation, and problem-solving in authentic contexts. Consequently, STEM serves as a powerful framework for improving science education by promoting experiential learning and enabling students to apply scientific knowledge in solving contemporary societal and technological problems.

The interdisciplinary nature of STEM education supports several contemporary instructional approaches, including inquiry-based learning, problem-based learning, project-based learning, engineering design, collaborative learning, and technology-enhanced instruction. These instructional approaches encourage learners to become active participants in constructing knowledge rather than passive recipients of information and prepare them to address real-world challenges through interdisciplinary thinking (UNESCO, 2021). Within science education, these approaches transform the classroom into an environment where learners actively investigate scientific phenomena, conduct experiments, analyse data, and design evidence-based solutions to practical problems.

One of the most significant contributions of STEM education is its ability to cultivate the four essential competencies commonly referred to as the 4Cs: Critical Thinking, Collaboration, Communication, and Creativity. These competencies have been identified as indispensable skills required for success in higher education, employment, entrepreneurship, and lifelong learning (OECD, 2023). Science education provides an ideal context for nurturing these

competencies because scientific investigations require learners to analyse evidence critically, work collaboratively in teams, communicate scientific ideas effectively, and develop creative solutions to scientific and environmental challenges.

Critical thinking enables learners to evaluate information objectively, analyse evidence, identify relationships, solve complex problems, and make informed decisions. Collaboration develops learners' ability to work productively with diverse individuals toward achieving shared goals. Communication equips students with the capacity to express ideas clearly using oral, written, visual, and digital formats, while creativity promotes innovation by encouraging learners to generate original ideas, develop multiple solutions, and improve existing designs (OECD, 2022). These competencies are increasingly recognised as fundamental outcomes of quality science education and integrated STEM instruction.

Through project-based investigations, engineering challenges, laboratory experiments, coding activities, robotics, and technology-supported learning, STEM education creates opportunities for students to integrate these competencies while addressing authentic societal challenges. Consequently, learners become innovative problem-solvers capable of contributing meaningfully to scientific advancement, technological innovation, sustainable development, and national economic growth.

Therefore, integrating STEM education into science education and classroom instruction is increasingly viewed as a strategic approach for fostering critical thinking, collaboration, communication, and creativity among learners. This seminar examines how STEM education contributes to the development of these four competencies and discusses its implications for improving science education, teaching and learning, and preparing learners to thrive in an increasingly technological and innovation-driven world.

Statement of the Problem

Despite the growing recognition of STEM education as an effective approach for improving science education and developing twenty-first-century competencies, many science classrooms continue to rely on traditional teacher-centred instructional methods that emphasise memorisation and examination performance

rather than inquiry, innovation, and real-world problem-solving. Consequently, many learners demonstrate limited abilities in critical thinking, collaboration, communication, and creativity, which are essential for addressing contemporary scientific, technological, environmental, and societal challenges. Furthermore, inadequate integration of science, technology, engineering, and mathematics, coupled with challenges such as insufficient teacher preparation, inadequate instructional resources, and limited technological infrastructure, has constrained the effective implementation of STEM education in many schools. This situation raises concerns about learners' preparedness to function effectively in an increasingly knowledge-driven and technology-orientated society. Therefore, there is a need to examine how integrating STEM education into science education can foster critical thinking, collaboration, communication, and creativity among learners, thereby enhancing scientific literacy, innovation, problem-solving abilities, and sustainable national development.

Concept of STEM Education

STEM education is an interdisciplinary approach to teaching and learning that integrates science, technology, engineering, and mathematics to solve authentic problems and improve students' understanding of real-world phenomena. Rather than teaching these disciplines separately, STEM education emphasises meaningful connections among them, enabling students to apply knowledge and skills in practical contexts (Ortiz-Revilla et al., 2021).

Within science education, STEM provides an instructional framework that enables learners to connect scientific concepts with technological applications, engineering design, and mathematical reasoning. This integration transforms science classrooms from environments focused primarily on memorising scientific facts into learner-centred settings where students investigate scientific phenomena, conduct experiments, solve real-life problems, and develop innovative solutions. According to UNESCO (2021), STEM education encourages learners to investigate scientific questions, apply mathematical reasoning, utilise technological tools, and engage in engineering design processes to solve complex real-life problems. This instructional approach develops cognitive, technical, collaborative, and innovative

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competencies required for sustainable development. Consequently, STEM education strengthens science education by promoting scientific literacy, inquiry, innovation, and practical application of scientific knowledge.

Roehrig, Dare, Ellis, and Ring-Whalen (2021) describe integrated STEM education as an educational approach that intentionally connects science, technology, engineering, and mathematics through authentic contexts to improve students' conceptual understanding, problem-solving ability, and twenty-first-century skills. In science education, this approach enables learners to understand scientific concepts more meaningfully by relating classroom learning to everyday experiences and societal challenges.

The major characteristics of STEM education in science education include interdisciplinary learning, inquiry-based instruction, problem-based learning, project-based learning and engineering design process

Concept of Critical Thinking in Science Education

Critical thinking refers to the ability to analyse information systematically, evaluate evidence objectively, interpret data accurately, and make reasoned decisions based on logical arguments. It involves reflective thinking, evidence-based judgement, and effective problem-solving (OECD, 2022).

Within science education, critical thinking enables learners to formulate scientific questions, design investigations, analyse experimental data, evaluate scientific evidence, identify relationships among variables, and draw valid conclusions. Through STEM education, science learners develop these competencies by engaging in inquiry-based investigations, engineering design activities, laboratory experiments, and authentic scientific problem-solving.

Concept of Collaboration in Science Education

Collaboration refers to the ability of individuals to work effectively with others toward achieving common goals through shared responsibilities, mutual respect, effective communication, and collective problem-solving. Integrated STEM learning environments promote collaboration by engaging learners in teamwork,

engineering design projects, laboratory investigations, and interdisciplinary problem-solving activities (English, 2023).

Within science education, collaboration enables students to conduct laboratory experiments, share scientific ideas, interpret results collectively, and design solutions to scientific and environmental problems. Working collaboratively helps learners develop teamwork, leadership, interpersonal communication, and shared decision-making skills that are essential for scientific research and innovation.

Concept of Communication in Science Education

Communication is the process of exchanging ideas, information, scientific findings, and solutions through oral, written, visual, and digital means. Effective communication enables learners to explain scientific concepts, defend arguments with evidence, interpret findings, and present innovative solutions clearly (OECD, 2023).

Within science education, communication is strengthened through laboratory reports, scientific presentations, classroom discussions, debates, poster exhibitions, project demonstrations, and the use of digital technologies. STEM learning provides authentic opportunities for learners to communicate scientific knowledge accurately while collaborating with peers to solve real-world problems.

Concept of Creativity in Science Education

Creativity refers to the ability to generate original, valuable, and innovative ideas for solving problems or improving existing products, systems, and processes. OECD (2022) describes creativity as a competency that enables learners to develop new ideas, explore alternatives, and produce meaningful solutions in unfamiliar situations.

Within science education, creativity enables learners to design experiments, develop scientific models, construct engineering prototypes, invent technological solutions, and apply scientific knowledge to address environmental and societal challenges. STEM education promotes creativity by encouraging learners to

investigate problems, experiment with multiple solutions, improve engineering designs, and apply innovative thinking to authentic scientific situations.

STEM Education and the Development of Critical Thinking in Science Education

Critical thinking is widely recognised as one of the most essential competencies required for success in the twenty-first century. It encompasses the ability to analyse information, evaluate evidence, interpret data, make logical inferences, solve complex problems, and reflect on one's reasoning before making informed decisions. In contemporary science education, critical thinking has become a fundamental learning outcome because learners are increasingly expected to address scientific, technological, environmental, and societal challenges using evidence-based reasoning rather than memorisation (OECD, 2023).

Integrated STEM education provides a rich environment for developing critical thinking because it engages learners in authentic and interdisciplinary scientific problem-solving experiences. Rather than presenting scientific knowledge as isolated facts, STEM instruction encourages students to investigate scientific phenomena, formulate research questions, gather and analyse evidence, develop hypotheses, test possible solutions, and evaluate outcomes using scientific reasoning. Such learning experiences require learners to think systematically, question assumptions, and justify their conclusions with empirical evidence (Ortiz-Revilla et al., 2021).

One of the most effective ways STEM education develops critical thinking in science education is through inquiry-based learning. Inquiry-based instruction places learners at the centre of the learning process by encouraging them to ask scientific questions, conduct laboratory investigations, analyse findings, and communicate conclusions. Instead of receiving ready-made answers, students actively construct scientific knowledge through exploration and experimentation. This process strengthens analytical thinking, scientific reasoning, and evidence-based decision-making (UNESCO, 2021).

Similarly, problem-based learning (PBL) enables science students to solve authentic environmental, technological, and societal problems that often have

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multiple possible solutions. During these activities, learners identify scientific problems, collect relevant evidence, evaluate alternative explanations, and determine the most appropriate solutions. Such activities require higher-order thinking and enable learners to transfer scientific knowledge across different STEM disciplines.

The engineering design process also plays a significant role in promoting critical thinking within science education. Learners identify scientific problems, generate ideas, design prototypes, test solutions, evaluate results, and redesign products based on scientific evidence. Throughout this iterative process, students continuously analyse information, identify weaknesses, compare alternative solutions, and improve their designs, thereby strengthening reflective thinking and scientific reasoning (Roehrig et al., 2021).

Technology integration further enhances critical thinking in science education by providing learners with opportunities to collect, analyse, and interpret scientific data using digital technologies such as virtual laboratories, simulations, modelling software, coding platforms, sensors, and artificial intelligence applications. These technologies enable learners to visualise scientific concepts, evaluate multiple scenarios, and make evidence-based decisions while strengthening computational and analytical thinking.

Project-based STEM learning also contributes substantially to developing critical thinking in science education. Through long-term scientific investigations, learners explore meaningful questions, analyse data from multiple sources, evaluate competing scientific explanations, and refine their solutions based on evidence and peer feedback. These experiences cultivate scientific inquiry, intellectual curiosity, independent thinking, and lifelong learning habits.

Teachers play an indispensable role in fostering critical thinking in science education through STEM instruction. They design authentic scientific investigations, facilitate inquiry-based learning, encourage questioning, organise laboratory activities, provide constructive feedback, and guide learners in evaluating scientific evidence objectively. Rather than functioning solely as transmitters of scientific knowledge, teachers become facilitators who support learners' exploration, reasoning, reflection, and problem-solving. Consequently,

integrating STEM education into science education equips learners with the critical-thinking competencies required for scientific literacy, innovation, responsible citizenship, and sustainable national development.

Strategies for Developing Critical Thinking through STEM Education in Science Education

Science teachers can foster critical thinking through STEM education by adopting learner-centred instructional strategies that promote inquiry, analysis, and evidence-based reasoning. These include:

- i. Implementing inquiry-based learning that encourages students to formulate scientific questions, conduct investigations, and draw evidence-based conclusions.
- ii. Engaging learners in problem-based learning using authentic scientific, environmental, and community issues.
- iii. Incorporating engineering design challenges that require planning, testing, evaluating, and redesigning scientific solutions.
- iv. Integrating computational thinking, coding, simulations, virtual laboratories, and other digital technologies into science instruction.

STEM Education and the Development of Collaboration in Science Education

Collaboration is one of the essential twenty-first-century competencies that prepares learners for scientific research, technological innovation, and professional practice. In science education, collaboration refers to learners' ability to work effectively with others in conducting investigations, sharing responsibilities, exchanging ideas, solving scientific problems, and developing innovative solutions. Since modern scientific discoveries and technological innovations are largely achieved through teamwork, science education must intentionally cultivate collaborative skills among learners (OECD, 2023).

Integrated STEM education naturally promotes collaboration because learners participate in inquiry-based investigations, laboratory experiments, engineering design challenges, robotics activities, coding projects, and project-based learning. These activities require students to work cooperatively by

identifying problems, planning investigations, collecting and analysing data, constructing prototypes, evaluating results, and communicating findings. Such collaborative experiences strengthen teamwork, leadership, communication, mutual respect, and collective decision-making while improving conceptual understanding of science (English, 2023).

Project-based learning is one of the most effective strategies for promoting collaboration in science education. Through collaborative projects, learners investigate authentic scientific and environmental problems, share responsibilities, and jointly develop practical solutions. Likewise, the engineering design process encourages students to brainstorm ideas, construct prototypes, test designs, evaluate outcomes, and improve products collectively, thereby strengthening interpersonal and problem-solving skills (Roehrig et al., 2021).

Technology integration further enhances collaboration by enabling learners to communicate and work together through digital platforms, virtual laboratories, collaborative simulations, cloud-based applications, and online discussion forums. These technologies prepare students for modern scientific practice, where research and innovation increasingly depend on digital collaboration and interdisciplinary teamwork (UNESCO, 2021).

Science teachers play a vital role in developing collaboration by organising cooperative learning groups, facilitating laboratory investigations, monitoring group participation, encouraging equal contributions, and providing constructive feedback. Through authentic STEM experiences, learners develop teamwork, responsibility, leadership, adaptability, and conflict-resolution skills that are essential for scientific inquiry, lifelong learning, and future careers.

Strategies for Developing Collaboration through STEM Education in Science Education

Science teachers can strengthen collaborative skills by:

- i. Organising learners into diverse cooperative groups with clearly defined responsibilities.
- ii. Implementing project-based learning that requires teamwork in solving authentic scientific problems.

- iii. Engaging students in collaborative laboratory investigations and engineering design challenges.
- iv. Integrating digital collaboration tools such as virtual laboratories, cloud-based platforms, and online discussion forums.
- v. Promoting peer assessment, group presentations, and reflective discussions to encourage accountability and teamwork.

STEM Education and the Development of Communication in Science Education

Communication is a fundamental twenty-first-century competency that enables learners to express scientific ideas clearly, interpret evidence, present research findings, and engage in meaningful discussions using oral, written, visual, and digital formats. In science education, communication is essential because scientific knowledge is developed and shared through observation, experimentation, argumentation, and evidence-based explanations (OECD, 2023).

Integrated STEM education strengthens communication by engaging learners in inquiry-based investigations, laboratory experiments, engineering design, project-based learning, and collaborative problem-solving. These activities require students to formulate scientific questions, discuss ideas, analyse experimental data, prepare laboratory reports, present findings, and defend conclusions using scientific evidence (Ortiz-Revilla et al., 2021). Through these experiences, learners develop scientific literacy, confidence, and effective communication skills.

Technology further enhances communication in science education through virtual laboratories, digital portfolios, multimedia presentations, online discussions, and collaborative learning platforms. Teachers facilitate this process by encouraging classroom discussions, scientific debates, presentations, and constructive feedback while using authentic assessments such as laboratory reports, project presentations, and reflective journals to evaluate learners' communication skills (UNESCO, 2021; English, 2023).

Strategies for Developing Communication through STEM Education in Science Education

- i. Encourage inquiry-based discussions and scientific argumentation.
- ii. Organize project-based learning involving laboratory reports and oral presentations.
- iii. Engage students in engineering design presentations and peer review.
- iv. Integrate digital technologies such as virtual laboratories, simulations, collaborative platforms, and multimedia tools.
- v. Promote science fairs, exhibitions, debates, and poster presentations.

Strategies for Integrating STEM Education in Science Education

Successful STEM integration requires transforming science classrooms into learner-centred environments where students actively investigate scientific problems and apply interdisciplinary knowledge. Teachers should adopt inquiry-based learning, project-based learning, engineering design, collaborative learning, and technology-enhanced instruction to connect scientific concepts with real-life situations (UNESCO, 2021).

Effective integration also requires modern laboratories, digital technologies, robotics, coding activities, simulations, authentic assessment, and continuous teacher professional development. Collaboration among schools, universities, industries, and communities further enriches science learning by exposing students to authentic scientific and technological experiences (OECD, 2023).

Benefits of Integrating STEM Education into Science Education

Integrating STEM into science education improves students' conceptual understanding by linking scientific knowledge with practical applications. It enhances critical thinking, creativity, communication, collaboration, scientific inquiry, technological competence, and problem-solving skills. STEM also increases learners' motivation, curiosity, innovation, and career readiness for science, engineering, technology, healthcare, and other STEM-related professions (Roehrig et al., 2021).

Beyond the classroom, STEM education contributes to scientific literacy, entrepreneurship, environmental sustainability, technological advancement, and national development by preparing learners to solve real-world scientific and societal challenges (UNESCO, 2021).

Challenges of Integrating STEM Education into Science Education

Despite its benefits, STEM implementation in science education faces several challenges. These include inadequate teacher preparation, insufficient laboratories and instructional materials, poor internet access, limited technological facilities, overcrowded classrooms, rigid curricula, inadequate funding, and examination-oriented teaching practices (OECD, 2023).

Other barriers include limited opportunities for professional development, insufficient collaboration among STEM disciplines, and resistance to innovative teaching methods. Addressing these challenges requires increased investment in STEM infrastructure, curriculum reform, teacher training, and supportive educational policies.

Implications for Teaching and Learning in Science Education

Integrating STEM education requires science teachers to move from teacher-centred instruction to learner-centred approaches that emphasise inquiry, collaboration, experimentation, creativity, and authentic problem-solving. Teachers become facilitators who guide learners in conducting scientific investigations, designing engineering solutions, and applying technology to solve real-world problems.

For learners, STEM education promotes active participation, independent learning, teamwork, innovation, and lifelong learning. Curriculum developers should design flexible science curricula that integrate interdisciplinary learning, digital technologies, and authentic assessment to develop both scientific knowledge and twenty-first-century competencies.

Conclusion

Integrating STEM education into science education provides an effective framework for preparing learners for the demands of the twenty-first century. By combining science, technology, engineering, and mathematics through inquiry, project-based learning, engineering design, and technology integration, STEM develops learners' critical thinking, collaboration, communication, and creativity. These competencies equip students to become scientifically literate, innovative problem-solvers capable of addressing contemporary scientific, technological, environmental, and societal challenges. Therefore, strengthening STEM integration in science education is essential for improving educational quality, promoting sustainable development, and preparing learners for future careers in an increasingly technology-driven world.

Recommendations

- i. Governments should strengthen the integration of STEM education into science education curricula at all educational levels.
- ii. Schools should provide well-equipped science laboratories, digital technologies, robotics kits, internet facilities, and other STEM resources.
- iii. Continuous professional development should be organised to equip science teachers with modern STEM pedagogies and digital competencies.
- iv. Science teachers should adopt inquiry-based, project-based, collaborative, and engineering design approaches to foster learners' critical thinking, communication, collaboration, and creativity.
- v. Assessment should emphasise authentic tasks such as laboratory investigations, projects, presentations, portfolios, and engineering design rather than relying mainly on written examinations.
- vi. Educational institutions should establish partnerships with industries, research institutes, and universities to provide authentic STEM experiences and strengthen science education.

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