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Connecting the dots: Science and mathematics knowledge as predictors of stem education conceptions in preservice primary teachers

Agustiningsih[*], I Ketut Mahardika, Singgih Bektiarso, Nuriman
Faculty of Teacher Training and Education,University of Jember, Indonesia

***Corresponding author:** ningsihagustin83.fkip@unej.ac.id

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Abstract

Science, technology, engineering, and mathematics (STEM) education is an interdisciplinary approach that has gained global recognition for its potential to develop higher-order thinking and practical skills to address real-world challenges. In the context of teacher preparation, STEM education is particularly important for preservice primary school teachers who are expected to develop meaningful and integrated learning experiences in the classroom. However, limited research has examined how science content knowledge (SCK) and mathematics content knowledge (MCK) shape preservice teachers' conceptions of STEM education, particularly in the Indonesian context. This research investigated the relationship between science content knowledge and mathematics content knowledge in relation to the preservice primary school teachers' conceptions of STEM education. The survey method was used to collect data about science content knowledge, mathematics content knowledge, and STEM conceptualizations. A total of 139 preservice primary school teachers participated in this study. The data were analyzed using two way between-group analysis of variance (ANOVA) with IBM SPSS 25. These results suggest that strong disciplinary knowledge in science and mathematics forms an essential foundation for meaningful STEM understanding. The results indicate that science and mathematics content knowledge can influence preservice primary school teachers' conceptions of STEM education. The study has important implications for teacher education, indicating that preservice teacher programs should strengthen disciplinary coursework while systematically integrating STEM pedagogy and interdisciplinary learning experiences to better prepare future teachers for effective STEM implementation in primary education.

Introduction

Science, technology, engineering, and mathematics (STEM) education is an interdisciplinary approach that has gained global recognition for its potential to develop higher-order thinking and practical skills to address real-world challenges. Beyond fostering cognitive abilities, STEM education enhances collaboration, creativity, and problem-solving through contextual, project-based integration of disciplines (Cao, X., Li, Y., & Zhang, H., 2025). This approach emphasizes the application of knowledge in authentic contexts to establish meaningful connections across fields. Recent studies indicate that STEM learning experiences can strengthen students' interest and career aspirations in STEM and influence the relationship between self-concept and perceptions of STEM professions (Chen et al., 2024). Furthermore, STEM education has been shown to improve learning outcomes across educational levels by promoting interdisciplinary links and meaningful engagement (Frontiers in Education, 2026). Achieving these objectives requires educators to adopt teaching methods that support active, reflective, and contextualized learning. To achieve this goal to benefit students, educators need to change their teaching style.

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In Indonesia, the integration of STEM into school curricula has become increasingly important as the education system seeks to equip students with 21st-century competencies, including critical thinking, communication, collaboration, and creativity (Ng, 2019; Enhancing 21st Century Skills through Integrated STEM Education, 2024). Preservice teachers, particularly at the primary level, play a key role in this effort because they are responsible for introducing foundational concepts across multiple subjects (Menon et al., 2023). Their ability to implement STEM approaches depends not only on their pedagogical skills but also on the depth and integration of their science and mathematics content knowledge (Menon & Azam, 2021; Menon et al., 2024). Understanding how content knowledge relates to preservice teachers' STEM conceptions is therefore essential for designing effective teacher education programmes (Menon et al., 2023; Preservice Elementary Teachers' Integrated STEM Teaching Self-Efficacy, 2025).

STEM integration involves a multidisciplinary approach that connects science, technology, engineering, and mathematics to support students in addressing complex real-world problems through authentic learning experiences, inquiry, and project-based activities (Margot & Kettler, 2021). Despite its growing recognition as an effective approach to promote interdisciplinary learning, the implementation of integrated STEM education remains challenging in classroom contexts. Teachers often face difficulties related to pedagogical knowledge, curriculum coherence, instructional planning, assessment practices, and institutional support (Kelley & Knowles, 2022; Thibaut et al., 2022; Zhang et al., 2024). These challenges indicate that successful STEM integration requires more than teachers' willingness to adopt STEM approaches; it requires a systematic understanding of how disciplinary knowledge can be meaningfully connected, integrated, and transformed into coherent learning experiences through appropriate curriculum design and instructional practices (Roehrig et al., 2021; Tytler et al., 2023).

STEM education requires educators to design interdisciplinary learning experiences that engage students in addressing complex and authentic problems, as the integration of science, technology, engineering, and mathematics provides opportunities for meaningful connections among disciplinary concepts (Kelley et al., 2021; Roehrig et al., 2021). Effective STEM implementation also requires coherent curricular frameworks and instructional structures that clarify how different STEM disciplines are connected and applied within lessons and learning units (Roehrig et al., 2021; Huang et al., 2022). In this context, teachers are expected to facilitate students' participation in inquiry, engineering design, modeling, problem-solving, evidence-based reasoning, data analysis, mathematical applications, and communication of scientific ideas as essential components of integrated STEM learning (Andrews et al., 2022; Huang et al., 2022).

Energy is an important concept that can support integrated STEM learning because it provides meaningful connections among multiple scientific disciplines and engineering practices. Energy functions as a crosscutting concept that enables learners to explain phenomena across physical science, life science, Earth and environmental science, and engineering by examining processes of energy transformation, transfer, and conservation (National Academies of Sciences, Engineering, and Medicine, 2021; Roehrig et al., 2021). In biology, energy concepts are essential for understanding photosynthesis, cellular respiration, and energy flow within ecosystems, whereas in physics and chemistry, energy provides a framework for explaining interactions, changes in matter, motion, heat, and chemical processes. In engineering contexts, energy knowledge supports the design, evaluation, and optimization of systems involving energy conversion, storage, and sustainable solutions (Kelley et al., 2021; Tytler et al., 2023). Therefore, developing preservice teachers' energy content knowledge can serve as a foundation for connecting disciplinary concepts and designing coherent integrated STEM learning experiences.

The concept of energy in Indonesia's curriculum begins in primary school and continues through secondary education. Because primary teachers are responsible for introducing foundational scientific ideas, preservice primary teachers need strong energy content knowledge to support effective science teaching practices. A robust understanding of energy concepts is essential for developing integrated STEM learning activities because such learning requires teachers to connect scientific concepts with technological applications, mathematical reasoning, and engineering design practices (Kwon & Kwon, 2022; Roehrig et al., 2021). Limited understanding of energy concepts may constrain teachers' ability to design coherent STEM learning experiences that integrate disciplinary knowledge and support students' problem-solving abilities (Kelley et al., 2021; Wahono et al., 2022).

Previous research has demonstrated that preservice teachers' understanding of STEM education plays an important role in shaping their readiness to implement STEM approaches in classroom contexts. A comprehensive understanding of STEM enables preservice teachers to recognize the relationships among science, technology, engineering, and mathematics and to develop meaningful connections across disciplinary boundaries (Kelley et al., 2021; Roehrig et al., 2021). Preservice teachers' STEM understanding should extend beyond defining STEM as an acronym and include awareness of its educational purposes, interdisciplinary characteristics, and potential applications in teaching and learning (Huang et al., 2022; Li et al., 2022). Furthermore, well-developed STEM understanding can support preservice teachers in designing learning experiences that are contextual, inquiry-based, and connected to authentic real-world problems (Roehrig et al., 2021; Tytler et al., 2023).

Although STEM education has been widely discussed, limited studies have examined how preservice primary teachers conceptualize STEM education in relation to their disciplinary content knowledge, particularly in developing contexts such as Indonesia. This issue is important because future primary teachers are expected to facilitate integrated learning across subject areas. If preservice teachers have insufficient science or mathematics content knowledge, they may experience difficulties in designing STEM learning activities that meaningfully connect disciplinary concepts, scientific and engineering practices, and authentic real-world problems (Roehrig et al., 2021; Wahono et al., 2022). Furthermore, preservice teachers' understanding of STEM integration is closely related to their ability to recognize interdisciplinary connections and transform content knowledge into coherent STEM learning experiences (Kelley et al., 2021; Li et al., 2022).

The aim of this research is to investigate content knowledge and skills in science and mathematics to understand the STEM concept in preservice primary school education in Indonesia. This research is guided by this question: what is the relationship between science content knowledge, mathematics content knowledge, and the understanding of STEM education for preservice primary school teachers? The result of this research is expected to support the preparation of the preservice teachers who will use the STEM education approach in the classroom. In addition, it might also shed light on how teachers can master content knowledge to be able to develop the STEM instructional materials. The following section discusses the concept of STEM integration, then presents energy content knowledge as a component of STEM educational materials, and finally examines preservice teachers' interpretations of STEM education.

STEM Integration

STEM integration involves a multidisciplinary approach to science, technology, engineering, and mathematics and is widely viewed as a way to engage students in solving real-world problems through authentic tasks and projects (Ng, 2019). However, the integration of STEM subjects remains challenging and complex in classroom implementation, with teachers reporting difficulties related to pedagogy, curriculum alignment, and structural constraints. Recent studies on integrative STEM practices emphasize exploratory, problem-centered approaches in which learning activities connect two or more STEM disciplines, and sometimes link STEM with other school subjects, to reflect the multidisciplinary nature of real-world issues. Integrated STEM instruction is also described as a natural avenue for developing students' abilities to use science, mathematics, and engineering to address complex problems and to cultivate critical thinking and collaboration (Ng, 2019; Enhancing 21st Century Skills through Integrated STEM Education, 2024). At the same time, research indicates that many teachers recognize the potential of STEM integration and express strong interest in using it as a classroom strategy, but they vary widely in how they conceptualize STEM and in the extent to which they implement genuinely integrated activities.

STEM education requires that educators create activities to solve emerging and often complex problems in the classroom, which may be difficult to address when subjects are taught separately. It also demands clear curricular and instructional structures that guide how science, technology, engineering, and mathematics will work together within coherent lessons and units. In this context, teachers are expected to facilitate students' engagement with scientific and engineering practices, including asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and communicating information, as emphasized in recent work on NGSS-aligned classrooms. At the same time, educators must build connections between big ideas, address students' misconceptions, integrate digital technologies, and establish real-world and culturally relevant links, which together require strong capacity to manage complex, integrated STEM instruction effectively.

Professional development for STEM teachers has been widely investigated in recent years, and numerous models have been implemented across different countries and institutions to strengthen teachers' capacity for integrated STEM instruction. However, evidence from recent reviews shows that the needs of STEM teachers continue to grow, particularly in terms of interdisciplinary content knowledge, pedagogical strategies for integration, and confidence in designing STEM learning experiences. To address these needs, it is increasingly argued that preservice teachers should begin developing a robust and coherent understanding of STEM education during their initial teacher education, rather than relying solely on in-service professional development (Preservice Elementary Teachers' Integrated STEM Teaching Self-Efficacy, 2025). Although research on preservice teachers' roles in supporting STEM programmes is expanding, recent studies still highlight gaps in their opportunities to engage deeply with integrated STEM design tasks and school-based implementation during university programmes (Enhancing Preservice Teachers' STEM Self-Efficacy, 2025). Incorporating STEM education explicitly into university curricula—through dedicated STEM methods courses, integrated field experiences, and design-based projects—has been shown to help preservice teachers develop a more profound and practice-oriented understanding of STEM (Preservice Elementary Teachers' Integrated STEM Teaching Self-Efficacy, 2025). Within this process, mastery of disciplinary content knowledge remains a central priority because it underpins preservice teachers' self-efficacy and confidence in developing and enacting STEM instructional materials in their future classrooms (Enhancing Preservice Teachers' STEM Self-Efficacy, 2025).

Energy Content Knowledge

Energy is identified in the Next Generation Science Standards as a central disciplinary core idea that spans physical science, life science, Earth science, and engineering, making it a unifying theme across K–12 curricula (NGSS Lead States, 2013). In biology, the idea of energy is fundamental for explaining processes such as photosynthesis and cellular respiration, where light energy is transformed into chemical energy and then redistributed through organisms and ecosystems (NGSS Lead States, 2013). In physics, energy provides a framework for describing motion, interactions, and the conservation of energy within and between systems, while in chemistry it helps to interpret how chemical reactions involve the breaking and forming of bonds accompanied by energy changes (NGSS Lead States, 2013). In engineering, energy concepts guide the design and optimization of solutions, for instance by increasing the efficiency of devices and systems that transform, store, or transfer energy under given constraints. Taken together, these perspectives position energy not only as a core disciplinary idea but also as a crosscutting concept that allows students to track flows, transformations, and conservation of energy across diverse scientific and technological contexts (NGSS Lead States, 2013).

Driver, Asoko, Leach, Scott, & Mortimer (1994) rank the concept of energy on a scalefrom simple to complex, ranging from energy transformation to energy dissipation and energyconservation. Some researchers (Putra & Kumano, 2018; Yao, Guo, & Neumann, 2017) have used this scale as an instrument for evaluating the energy progression; they have suggested that energy instruction should not be solely organized around key concepts about energy but make use of the STEM subjects to link the key ideas to each other.

The concept of energy in Indonesia's curriculum starts from the primary school and continues to senior high school. According to Yao et al. (2017), the primary curriculum focuses on the concept of energy transformation and culminates in energy conservation in the senior high school. This research concentrates on the concept of energy, mainly because energy has always been the main focus of Indonesia's curriculum, requiring that preservice primary teachers improve their understanding of energy content knowledge.

Preservice Teaching Experience in STEM Education

In a study, Radloff & Guzey (2016) sought the views of preservice teachers on STEM education; they concluded that STEM education can facilitate preservice teachers' understanding of STEM. The researchers distributed open-ended questionnaires to the preservice science teachers in some universities to gain insights about STEM education. The findings illustrated that the preservice teachers who intended to apply STEM education in the classroom should start from a definite, concerted, and visual understanding of STEM education. Similarly, Bybee (2013) has explained that perspectives on STEM should beincluded in its definition and appropriate connections be made between the elements ofSTEM education. Bybee has introduced nine possibilities of visualization about STEM education. Other researchers, such as Yildirim & Sevi (2016), are of the opinion that the perspectives on STEM education can help preservice teachers improve their imagination. Preservice teachers' proper understanding of STEM education can generally have a positive effect on STEM education practices (Erdogan & Ciftci, 2017). In another research, Radloff & Selcen (2017) asked the preservice teachers to observe and analyze a video showing STEM learning. The preservice teachers who had some knowledge about STEM education subsequently expressed interest to apply STEM education in the classroom.

Recent findings further suggest that preservice teachers' perspectives and visualizations of STEM such as how they imagine the relationships among science, technology, engineering, and mathematics, or how they represent STEM in drawings and lesson plans - play an important role in shaping their ability to design meaningful integrated learning experiences. Studies have documented that richer, more connected visual and conceptual representations of STEM are associated with greater creativity and flexibility in lesson design, as well as increased willingness to use open-ended, project-based activities. In addition, research on preservice teachers' self-efficacy for integrated STEM teaching indicates that programmes which combine conceptual work on "what STEM is" with guided opportunities to analyse STEM lessons, observe STEM teaching (e.g., via video), and design their own integrated units can significantly enhance their confidence and readiness to enact STEM practices in classrooms (Preservice Elementary Teachers' Integrated STEM Teaching Self-Efficacy, 2025). Together, these studies reinforce the idea that a well-developed understanding of STEM grounded in both conceptual clarity and rich representations - can positively influence preservice teachers' STEM teaching practices.

This study holds that an understanding of STEM education for preservice teachers is a necessary foundation for applying STEM in the classroom. The limited research on preserviceteachers' understanding of STEM education justifies the focus of this research, which is onthe preservice primary school teachers' preparation for STEM education in Indonesia's curriculum.

Method

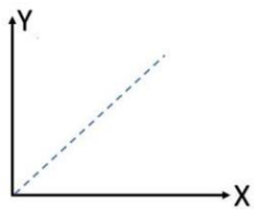
Research Approach

A survey method was used to explore the primary school preservice teachers' understanding of STEM education in the University of Jember, Indonesia. Questionnaires have several advantages. For example, all the responses fall into categories that have been designed beforehand by the researcher, and the respondent finds the questions easy and relatively quick to answer (Newby, 2014). A total of 139 participants (male = 27 and female =112). The participants were all in the third year of a four-year preservice primary education programme. The survey was conducted in 2026 summer semester. The participants studied both science and mathematics as well as social and art subjects. The total credit for this programme is 30 of 144, which contains topics relating to science (11 credits), technology (2 credits), engineering (2 credits), and mathematics (15 credits). There is also a total credit of 52 (of 144) in educational psychology to support the preservice primary teachers' knowledge about children's behaviour and learning theory.

Instruments

The instruments used in this study assessed science content knowledge, mathematic content knowledge and the preservice primary teachers' understanding of the use of STEM education in the classroom. The science content knowledge consisted of eleven questions. The questions included STEM definition related to energy (three items), STEM relevance to energy (four items), STEM visualization related to energy (four items). The mathematic content knowledge consisted of eleven questions. The questions included STEM definition related to Algebra (three items), STEM relevance to Algebra (four items), STEM visualization related to to Algebra (four items). (see Table 1). The participants couldchoose between 'agree' or 'disagree' options, followed by a written opinion. The section relating to STEM understanding consisted of 11 questions for Science Content Knowledge (Topic: Energy) and of 11 questions for Mathematics Content Knowledge (Topic: Algebra). Three questions evaluated STEM definition, four questions evaluated STEM relevance, and four questions evaluated STEM visualization (Putra & Kumano, 2018).

Table 1. The Quetionary of Science and Mathematics Content Knowledge

Statement	Yes/No	Reason
Science Content Knowledge (Topic Energy)		
STEM Definition Related to Energy		
Energy is an appropriate topic for integrated STEM education because it connects concepts from science, technology, engineering, and mathematics		
Energy is a vector quantity because it can be summed algebraically.		
During an experiment, a student was looking at a piece of ice, which slowly changed into liquid in front of her eyes. This student wrote in her report that the ice melted and changed into liquid. Her statement is an observation. ('Data−PISA', 2015)		
STEM Relevance to Energy		
Learning energy through STEM education should involve understanding energy transformation, energy transfer, and energy applications rather than only memorizing scientific concepts		
STEM learning about energy requires students to integrate knowledge from different disciplines rather than learning energy only as a science topic.		
Energy concepts help students understand the relationship between scientific phenomena and real-world problems		
Science knowledge is important for students to understand and apply energy concepts in STEM learning activities		
STEM visualization related to energy		
Energy-based STEM learning should involve students in solving authentic problems related to everyday life		
Science, technology, engineering, and mathematics should be represented as interconnected components when teaching energy concepts.		
Understanding energy concepts requires students to recognize how energy changes from one form to another in different systems and applications.		
A deeper understanding of energy concepts can be developed by investigating how energy is transformed, transferred, and conserved in designed products and systems.		
Mathematics Content Knowledge (Topic: Algebra)		
STEM Definition Related to Algebra		
Is this true: 0.9999… = 1. Please explain by evidence (Kleickmann et al., 2013)		
 Based on the graphic above, the slope in the graph is equal to *y/x*.This statement is always true.		
Algebra is an important mathematical concept in STEM education because it represents relationships, patterns, and unknown quantities in various situations.		
STEM Relevance to Algebra		

Algebraic reasoning is useful for representing relationships among quantities in real-world STEM problems
Algebra knowledge supports data analysis, pattern recognition, prediction, and decision-making in STEM activities.
Algebra can be connected with science concepts through mathematical models, equations, and representations of relationships.
Strong algebra content knowledge is necessary for teachers to design effective integrated STEM learning activities.
STEM visualization related to energy
Algebra can be visualized as a tool for explaining and solving authentic problems in STEM learning.
STEM activities involving algebra should include representations such as variables, equations, graphs, or mathematical models
Algebraic concepts can support the design, evaluation, and improvement of technological or engineering solutions
Algebra serves as a bridge that connects mathematics with science, technology, and engineering in integrated STEM learning

Data Analysis

Two-way between-group analysis of variance (ANOVA) test (SPSS IBM 25) was utilized to analyze the data. Content knowledge was divided into three groups, based on the test results. The groups were identified as high, moderate, and low. The high group was for the participants who had a grade above average, and the low group was for the participants who had a grade below average. Each group was evaluated for STEM conceptualization.

Results

Table 2 shows the general results of the science and mathematics content knowledge for preservice primary school teachers. The mean of science content knowledge (SCK) is 72.61, SD 7.34, and the mean of mathematics content knowledge (MCK) is 70.50, SD 6.88. The mean illustrates the grade that has been obtained about the understanding of STEM education. The minimum score of STEM education conception is 43.00, and the maximum score is 80.00.

Table 2. Description of the Results of Preservice Primary School Teachers' Understandingabout STEM Education

	Group	N	Mean	SD
Science Content Knowledge	Low	57	65.28	0.99
	Moderate	73	69.63	0.54
	High	9	73.33	2.21
Maths Content Knowledge	Low	33	64.06	1.48
	Moderate	92	68.67	0.51
	High	14	73.79	1.47

Table 3. The ANOVA Result Analysis

Source	SE	df	MS	F	Sig.
Science Content Knowledge (SCK)	236.690	2	118.345	3.773	.026**

Maths Content Knowledge (MCK)	349.901	2	174.950	5.578	.005**
SCK* MCK	321.054	3	107.018	3.412	.020**
Total	650438.323	139			

R Squared = .308 (Adjusted R Squared = .271)
* interaction between variable
** Correlation significant at 0.05 level (2-tailed)

Table 3 presents the test results of between-subject effect about the understanding of STEM as the dependent variable. The results indicate three significant differences. First, thereare significant differences between the groups in SCK about the understanding of STEM education ($F(2.140) = 3.773$, $p = 0.026$). Second, there are significant differences between thegroups in MCK about the understanding of STEM education ($F(2.140) = 5.578$, $p = 0.005$). Finally, there is an interaction between SCK and MCK ($F(3.140) = 3.412$, $p = 0.020$). Table 4 presents the data distribution and illustrates that the highest mean for understanding STEM education belongs to the preservice primary school teachers who have high SCK and high MCK.

Table 4. Distribution between SCK and MCK

Dependent Variable	SCK	MCK	N	Mean	Std. Deviation
Understanding of STEM Education	Low	Low	16	60.1061	10.21619
		Medium	41	67.3112	4.96801
	Medium	Low	16	68.0492	4.19595
		Medium	48	69.8567	4.65507
		High	9	71.2896	5.17617
	High	Medium	4	68.2828	4.06934
		High	5	78.3030	2.55877

Discussion

The aim of this study was to explore the relationship between SCK and MCK in relation to preservice primary teachers' understanding of STEM conceptualization. The completed questionnaires described the preservice primary school teachers' SCK and MCK. The preservice primary school teachers answered the questions about their understanding of the STEM education approach, which included its definition, relevance, and visualization. This section discusses these results.

Our findings show that SCK and MCK can influence the preservice primary school teachers' understanding of STEM. Additionally, SCK and MCK interact with the preservice primary school teachers' understanding of the STEM education approach. This means that thepreservice primary school teachers who have a better mastery of SCK and MCK will find it easier to organize the materials in the STEM education approach. This finding resonates with Bruner's (1966) research result, in that prior knowledge and experience influence the understanding of the concept. The preservice primary school teachers' understanding ofSTEM education can form the basis of their current knowledge, which is constructed from thebasic idea, such as SCK and MCK. This same argument was presented by Ryu, Mentzer, & Knobloch (2018) who conducted STEM education professional development training for teachers. In the final part of the research, the teachers still connected STEM instruction with their academic background, even with what they had learnt in STEM training.

The training of preservice primary school teachers to implement STEM education maybegin with incorporating STEM subject knowledge into the curriculum. This study supports the idea that content knowledge, particularly SCK, should form the basis of teachers' mastery of science, so that teachers who have the content knowledge will also have the confidence teaching STEM effectively (Palmer et al., 2017; Palmer, 2006). Content knowledge enhanced by STEM education can increase confidence in STEM teaching, have a positive influence on attitudes towards science and science teaching, and develop potential ideas for STEM learning in the future (Menon & Sadler, 2017).

The interaction between SCK and MCK for understanding STEM education is crucial.The results of this research suggest that the preservice primary school teachers who scoredhigh in SCK and MCK demonstrated great understanding of the STEM education approach.The respondents indicated that they used the concept to manage the relationship between thesubjects, particularly science and mathematics. In a research, Wang (2013) has shown that thescience and mathematics courses are linked to students' intention of studying STEM. Whatdistinguish this research from others are its participants who were preservice primary schoolteachers. Having a complete understanding of content knowledge and STEM education canprepare preservice primary school teachers for the implementation of STEM in the classroom.

The focus on energy as a core topic provides an illustrative example of how strong content knowledge can support STEM thinking. Energy concepts inherently span biology, physics, chemistry, and engineering, which makes them particularly suitable for integrated STEM tasks and interdisciplinary projects, including those related to climate change, sustainability, and renewable energy technologies. Recent research on energy learning progressions indicates that both students and preservice teachers tend to move from intuitive, everyday notions of energy (for example, as "something that is used up" or "makes things work") toward more sophisticated understandings that emphasize energy transformation, conservation, and dissipation across different systems and contexts. Within this study, preservice teachers' energy content knowledge appears to function as a conceptual bridge that can support integrated STEM learning, enabling them to connect physical phenomena (such as motion, heat, and electric circuits), biological processes (such as photosynthesis and cellular respiration), and practical design problems involving energy efficiency and renewable energy solutions in ways that are consistent with current three-dimensional STEM education frameworks.

At the same time, the findings highlight ongoing challenges for preservice teacher preparation. While higher SCK and MCK are associated with stronger STEM conceptions, content knowledge alone does not guarantee that preservice teachers will be ready to design and implement rich STEM lessons, as many still struggle with confidence, beliefs, and practical strategies for integration (Menon et al., 2023). Recent studies with Indonesian and international preservice teachers show that a substantial proportion still view STEM primarily as an acronym or as a loose aggregation of subjects, and they report difficulties in translating the idea of integration into concrete classroom practices and tasks. This suggests that teacher education programmes need to go beyond disciplinary coursework by explicitly modelling integrated STEM pedagogy, providing examples of interdisciplinary and project-oriented units, and offering structured opportunities for preservice teachers to design, implement, and reflect on STEM lessons in both university and school-based settings (Menon et al., 2023; Enhancing 21st Century Skills through Integrated STEM Education, 2024).

The absence of significant gender differences in STEM understanding in this study also warrants discussion. International literature frequently reports gendered patterns in STEM interest and participation, with men more likely to pursue engineering or physical sciences and women often reporting lower self-efficacy or less positive self-concept in some STEM domains. In contrast, the present findings show similar levels of STEM understanding for male and female preservice primary teachers. One plausible explanation is the specific context of primary teacher education in Indonesia, where women are strongly represented in teacher education programmes and may engage with STEM primarily through a pedagogical rather than a career-choice lens, a pattern also observed in studies of early-childhood and primary preservice teachers in other countries. In such contexts, gender differences in STEM interest or identity may be less pronounced than in research focusing on engineering or science majors, even though subtle differences in self-efficacy profiles and preferred STEM roles (e.g., leadership in collaborative STEM projects) can still be detected.

From a practical standpoint, the results point to several implications for teacher education. First, programmes should intentionally strengthen preservice teachers' SCK and MCK through courses that foreground conceptual understanding and its application to authentic problems, as integrated STEM approaches have been shown to be more effective when teachers possess strong disciplinary foundations that they can connect to real-world design challenges. Second, integrated STEM experiences should be embedded across the curriculum, not limited to isolated workshops or single modules; research with preservice teachers indicates that sustained exposure to STEM tasks, collaborative design projects, and iterative reflective discussions improves both STEM content knowledge and pedagogical readiness for integration. Third, given the dominance of female preservice teachers in primary education, STEM initiatives should leverage this demographic reality by positioning STEM as a powerful tool for equitable, student-centred learning and social relevance rather than as a narrowly technical field, which can help broaden participation and align with broader goals of gender equity in STEM.

Finally, the findings contribute to the broader discussion on STEM teacher readiness in Indonesia. Recent reviews suggest that STEM research with Indonesian preservice teachers has expanded rapidly but that conceptions of STEM and models of implementation remain diverse and sometimes fragmented. This study adds empirical evidence that strengthening disciplinary content knowledge in science and mathematics can support clearer STEM conceptualizations among preservice primary teachers. However, it also underscores the need for integrated frameworks that connect content, pedagogy, and context, so that preservice teachers can move from understanding STEM in principle to enacting it in practice.

The findings of this study have several implications for teacher education institutions (LPTK) in Indonesia. First, the significant role of SCK and MCK in shaping preservice teachers' STEM understanding suggests that LPTK curricula should ensure a stronger alignment between disciplinary courses (science and mathematics) and integrated STEM experiences. This can be realized by redesigning science and mathematics courses so that they explicitly incorporate problem-based and project-based tasks that require students to apply concepts in authentic, interdisciplinary contexts. Second, LPTK need to move beyond treating STEM as an add-on topic and instead embed STEM integration systematically across multiple semesters. This could include dedicated STEM integration courses, school-based field experiences that focus on STEM lesson design and implementation, and capstone projects where preservice teachers collaboratively develop and test STEM units anchored in national curriculum content, such as energy in primary science. Third, national and institutional policies should support capacity-building for teacher educators themselves, through professional development in integrated STEM pedagogy and collaborative networks with schools, so that they can model high-quality STEM teaching for preservice teachers. In the long term, strengthening these structural and curricular supports in LPTK can contribute to more coherent and sustainable implementation of STEM education in Indonesian primary schools.

The results have several implications for teacher education institutions in Indonesia. First, science and mathematics courses should emphasize conceptual understanding and application to real-world problems. Second, STEM integration should not be treated as an additional topic, but embedded systematically across the teacher education curriculum. Third, teacher educators need professional development in integrated STEM pedagogy so that they can model effective STEM teaching practices. Finally, school-based experiences should be used to help preservice teachers connect STEM theory with classroom implementation.

These findings contribute to the broader discussion on STEM teacher readiness in Indonesia. The study provides empirical evidence that strengthening disciplinary content knowledge in science and mathematics can support clearer STEM understanding among preservice primary teachers. At the same time, the findings underline the need for integrated frameworks that connect content knowledge, pedagogical knowledge, and classroom context so that preservice teachers can move from understanding STEM in principle to implementing it in practice.

Conclusion

This research emphasizes that the understanding of STEM education can determine how preservice primary school teachers can master SCK and MCK. The interaction between SCK and MCK can facilitate the understanding of the STEM education approach. No significant difference of understanding between men and women in the STEM education approach was discerned. To gain a better understanding of STEM education among preserviceprimary school teachers, it is necessary to observe how preservice primary school teachers implement the STEM approach in their classroom teaching.This study found that science content knowledge and mathematics content knowledge are significantly related to preservice primary teachers understanding of STEM education. The results also show a significant interaction between science content knowledge and mathematics content knowledge, indicating that preservice teachers with strong knowledge in both areas demonstrate the highest level of STEM understanding. These findings suggest that integrated STEM understanding is supported by a strong disciplinary foundation in both science and mathematics. The study contributes to teacher education by highlighting the need to strengthen preservice theachers science and mathematics content knowledge while also integrating STEM pedagogy into teacher preparation programs. Teacher education institutions should provide structured opportunities for preservice teachers to connect disciplinary concepts, design interdisciplinary STEM lessons, and practice STEM teaching in authentic classroom contexts. Future research should examine how preservice teachers implement STEM approaches during classroom practice and how their content knowledge influences the quality of STEM lesson design and instruction.

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