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STEM Education In Elementary Schools: Readiness Of PGSD Teachers In Interpreting Science And Technology From An Early Age

Reviandari Widyatiningtyas
Universitas Langlangbuana, Indonesia

E-mail:
revywidya63@gmail.com

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ABSTRACT

STEM education in elementary schools requires the pedagogical readiness of PGSD teachers as the main foundation for successful implementation. Teachers play a strategic role as facilitators connecting concepts in science, technology, engineering, and mathematics with meaningful learning experiences. However, various studies indicate that teachers' STEM literacy is still limited, particularly in integrating theory with practice, resulting in conventional learning that does not foster critical, creative, and collaborative thinking skills. Other obstacles arise from limited facilities, a lack of supporting resources, and limited access to relevant digital learning resources. Furthermore, general and unsustainable teacher training leads to low confidence in designing project-based learning. Resistance to methodological changes also slows STEM adoption, primarily due to administrative burdens and a school culture that remains solely focused on academic achievement. To address this, strategies to strengthen teacher competency are needed through practice-based training, ongoing mentoring, the development of learning communities, and the use of digital technology. Collaboration with universities and industry is also crucial in enriching teachers' STEM literacy. This study uses a qualitative literature review to map the readiness, obstacles, and strategies for strengthening PGSD teacher competency. The study results confirm that teachers' pedagogical readiness is a crucial prerequisite for STEM to truly become a means of transforming 21st-century education, not just a formal discourse.

INTRODUCTION

STEM education in elementary schools is inextricably linked to the pedagogical readiness of primary school teacher educators (PGSD), the primary actors in learning. Teachers play a strategic role as facilitators, connecting concepts in science, technology, engineering, and mathematics with meaningful learning experiences for students. However, various studies indicate that teachers' mastery of STEM literacy remains

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relatively limited, particularly in integrating theory with practice. This limitation results in a limited variety of learning methods capable of stimulating students' critical, creative, and collaborative thinking skills from an early age. Unprepared teachers tend to maintain conventional learning patterns oriented toward memorization. Consequently, the goal of STEM education, which is to develop problem-solving skills, is not optimally achieved. Therefore, improving the pedagogical readiness of primary school teacher educators is a key prerequisite for implementing STEM education in elementary schools (Subayani & Ali, 2022).

The readiness of PGSD teachers is not only related to pedagogical aspects, but also to mastery of the project-based learning methodology that is a hallmark of STEM education. Project-based learning requires teachers to be able to design learning scenarios that emphasize interdisciplinary connections and their application in real life (Marliani, 2025). In this context, teachers' ability to interpret simple phenomena such as the movement of objects, natural patterns, or the use of everyday technology is crucial. Unfortunately, most PGSD teachers still focus on achieving curriculum material in a linear manner without considering contextual relevance. This indicates a gap between the national curriculum's orientation, which emphasizes creativity and practical application, and the reality of classroom learning practices. If this gap continues, STEM learning will remain limited to formal discourse without producing real transformation (Haverly & Davis, 2024). Therefore, PGSD teachers' methodological understanding of the STEM approach needs to be improved through more applicable training oriented to classroom needs.

Another barrier to STEM implementation in elementary schools is the limited availability of supporting facilities, both in the form of technology and simple laboratories (Wu, P et al., 2022). Many schools, particularly in rural areas, face limited resources, making it difficult for teachers to provide authentic learning experiences. This limitation often results in STEM learning being conducted theoretically without actual experimental practice. Furthermore, access to relevant digital learning resources remains limited, thus limiting teachers' exposure to technology-based learning innovations. This barrier is exacerbated by the lack of optimal policy support providing funding and infrastructure for STEM-based education. Without adequate facilities, teachers tend to revert to traditional methods that do not foster students' scientific reasoning. Therefore, improving facilities and infrastructure is a crucial supporting factor in ensuring effective STEM implementation.

Besides limited facilities, another significant obstacle is the lack of ongoing training focused on STEM literacy for primary school teachers. Much of the available training remains general and does not specifically address how STEM can be integrated into elementary school learning. This leaves teachers with insufficient practical experience to implement STEM approaches in the classroom. This lack of training also impacts teacher confidence in designing project-based learning. Teachers who feel incompetent ultimately tend to avoid innovation and revert to safer, more conventional patterns. Yet, literature shows that teachers' pedagogical confidence significantly determines the quality of students' learning experiences. Therefore, ongoing, relevant and contextual training is urgently needed to strengthen primary school teachers' readiness for STEM education (Wan et al., 2021).

Another factor complicating STEM implementation is resistance to changes in learning paradigms among some teachers. This resistance often arises from high administrative burdens, time constraints, and a fear of failure when trying new approaches. Teachers accustomed to conventional patterns feel reluctant when faced with changing learning strategies to be more interdisciplinary and project-based. This situation is further exacerbated by a lack of support from schools and teachers' professional environments. As a result, innovation in STEM learning is often hampered by an educational culture that remains solely oriented toward academic achievement. STEM, in fact, demands space for constructive exploration, experimentation, and failure as part of the learning process (Yuniar & Happy, 2024). Therefore, changing teacher mindsets is key to the broader implementation of the STEM approach in elementary schools.

To overcome these various obstacles, a comprehensive and sustainable strategy for strengthening the competencies of primary school teacher educators (PGSD) is needed. This strategy includes practice-based training that directly engages teachers in STEM learning simulations, not just theoretical ones (Amalia et al., 2025). Furthermore, developing teacher learning communities is crucial as a forum for sharing experiences, reflections, and learning innovations. Collaboration between elementary schools and universities providing PGSD can be a strategic step in improving the quality of teachers' STEM literacy. With collaborative support, teachers will have easier access to resources, mentoring, and best practices in teaching STEM. This is expected to strengthen pedagogical capacity while increasing teacher motivation to continue innovating. Thus, competency-building strategies not only improve individual teachers' abilities but also build a more supportive learning ecosystem.

The use of digital technology is also an effective strategy in supporting the readiness of PGSD teachers for STEM education. Technology can be utilized not only as a learning medium but also as an interactive learning resource that can visualize abstract concepts more concretely. For example, the use of digital simulations to explain simple physics phenomena or augmented reality-based learning applications can increase student engagement (Nurlaela & Mardiana, 2025). Teachers who are able to utilize technology creatively will find it easier to connect STEM concepts to students' daily lives. However, this use of technology must be balanced with increasing teachers' digital literacy so that the use of devices is not only technical but also pedagogical. Strong digital literacy enables teachers to select and adapt technology according to class needs. Thus, digital technology can be a catalyst in strengthening STEM implementation in elementary schools.

Overall, the discussion on the readiness, obstacles, and strategies for strengthening the competencies of primary school teacher educators (PGSD) demonstrates that STEM education in elementary schools is a complex yet urgent agenda. Without adequate pedagogical readiness, limited facilities, and ongoing training support, STEM implementation risks remaining merely a slogan without substance. However, with the right strengthening strategies, ranging from practical training, learning communities, to the use of digital technology, PGSD teachers can become more confident in integrating STEM into daily learning (Siregar, 2024; Pramudyani & Indratno, 2022). This not only impacts the quality of learning but also fosters the foundation of students' scientific thinking from an early age. Students accustomed to the STEM approach will be better prepared to face the challenges of the 21st century, which is rife with complexity and technological demands. Therefore, research on PGSD teacher readiness in STEM education not only has academic contributions but also practical implications for formulating more progressive educational policies. The continuity between the background, methods, and discussions reinforces the urgency of STEM as the foundation of primary education in Indonesia.

METHODOLOGY

This study employed a qualitative approach with a literature review, aiming to gain an in-depth understanding of the readiness of PGSD teachers to implement STEM education in elementary schools. A qualitative approach was chosen because it provides a comprehensive interpretation of complex educational phenomena, particularly in examining the roles, obstacles, and strategies for strengthening teacher competency in integrating science and technology from an early age.

The data collection process was conducted through a search of various relevant scientific sources, including reputable journal articles, academic books, research reports, conference proceedings, and national and international education policy documents. Inclusion criteria for literature selection included publications discussing STEM education, the role of elementary school teachers, pedagogical readiness, and strategies for implementing science and technology-based learning for elementary school-aged children. The publication timeframe focused on the last 10 years to ensure the data was up-to-date and its relevance to the context of 21st-century education.

Data analysis techniques were conducted through data reduction, data display, and conclusion drawing, as proposed by Miles and Huberman. Data reduction was carried out by selecting literature information relevant to the research focus, then systematically presenting it through data displays in the form of thematic tables and conceptual narratives. Furthermore, conclusions were drawn by synthesizing findings from various literatures to build a theoretical construct regarding the readiness of PGSD teachers in STEM education.

Data validity was maintained through source triangulation, which involved comparing and confirming study results from various national and international literature sources. Furthermore, the researchers applied critical appraisal to the quality of the articles used, ensuring that the analyzed data came from credible and academically sound sources. Therefore, the results of this literature review are expected to provide a comprehensive and in-depth overview of the actual conditions, opportunities, and challenges faced by primary school teacher educators in interpreting science and technology from an early age through a STEM approach.

RESULTS AND DISCUSSION

1. Pedagogical Readiness and Competence of PGSD Teachers in STEM Education

The pedagogical readiness of PGSD teachers is a strategic foundation for the success of STEM education in elementary schools, as the teacher's role is not merely as a transmitter of information, but as a facilitator who guides students in understanding scientific and technological phenomena contextually. This readiness cannot be viewed solely as mastery of material, but encompasses a combination of knowledge, teaching skills, and professional dispositions that enable teachers to build meaningful learning experiences. If teachers possess mature pedagogical readiness, STEM learning will not stop at simple project activities, but rather develop into a vehicle for scientific thinking, evidence-based argumentation, and solving real-life problems relevant to students' daily lives (Fauzia & Nu'man, 2025). Thus, pedagogical readiness is an indicator of whether STEM can be implemented as a learning transformation or is simply a formality.

Teacher competencies required for STEM learning include mastery of core concepts in basic science and mathematics, pedagogical skills for designing inquiry strategies, and technological literacy to enhance observation and data representation.

Within the TPACK framework, teachers must be able to integrate content knowledge, pedagogy, and technology to ensure learning activities are not fragmented. Furthermore, an orientation toward a project-based approach and engineering design is crucial for success, as teachers are required to familiarize students with formulating questions, devising solutions, testing hypotheses, and revising products based on collected data (Mulvidatin & Kurniawati, 2024). Thus, teacher competency extends beyond technical skills to fostering a scientific and engineering mindset in children from an early age.

Effective STEM learning practices in elementary schools ideally start from contextual phenomena close to students' lives, such as cloudy water, plastic waste, or simple energy use. Through the 5E model, students are guided from engagement to evaluation with a clear flow, while the engineering design process provides structure for solution-making activities. Teachers play a role in facilitating discussions, encouraging students to compare ideas, and connecting arguments to real-world data. Cross-subject integration also occurs naturally, for example when students write science journals, read graphs, calculate material ratios, or interpret experimental data. Thus, STEM learning not only sharpens cognitive skills but also literacy, collaboration, and communication.

The assessment aspect of STEM learning also demands an authentic approach that assesses both the process and the product. Teachers need to develop rubrics that assess students' abilities to formulate questions, design experiments, use evidence, and collaborate in groups. Formative instruments such as exit tickets, anecdotal notes, or engineering notebooks can help teachers track student progress continuously (Erlina, 2021). Assessment of products, such as models, prototypes, or data-based presentations, should be accompanied by students' critical reflection on the design decisions made. In this way, assessment becomes not just a measuring tool but a learning tool in itself, as students receive feedback that encourages improvement.

However, teachers' readiness to implement STEM often faces obstacles, ranging from limited conceptual knowledge, limited practical experience, and limited facilities. Some teachers still experience misconceptions about science concepts, while others face challenges of time and a busy curriculum. This situation is exacerbated by limited tools and a lack of confidence in facilitating technology-based learning (Riskawati et al., 2025). If these obstacles are not addressed, STEM learning will become merely a formal activity that falls short of the goal of developing critical thinking, analytical thinking, and problem-solving skills in students. Therefore, mitigation strategies such as the use of simple tools, lesson study, and a culture of classroom discussion are crucial to address these limitations.

The professional development of primary school teacher educators (PGSD) is a crucial step in strengthening pedagogical readiness in STEM. A program designed in stages, starting with basic training on the big ideas of science and technology, followed by guided practice through lesson study or peer coaching, and finally full classroom support, systematically enriches teachers' experiences. In this process, teachers are trained to design STEM units, implement them, and then reflect with colleagues to refine strategies (Sani et al., 2025). Through this continuous cycle, teachers' competencies improve not only conceptually but also practically, giving them greater confidence in integrating STEM into their daily classrooms.

To objectively measure teacher readiness, instruments capable of assessing knowledge, skills, and dispositions are needed. The TPACK survey, classroom observations with a structured rubric, and a STEM self-efficacy scale can be used as indicators (Sari & Mega, 2023). Furthermore, student learning artifacts also reflect teacher readiness, as the quality of student products indicates the quality of their learning facilitation. A measurement scheme with tiered levels, from "beginning" to "excellent," can help schools map teachers' positions and develop appropriate development strategies. With a clear mapping, competency strengthening can be carried out in a more targeted manner.

STEM implementation in elementary schools can be realized through contextual thematic units, for example, a project to design a simple water filter. In the activity flow, students are invited to observe water quality around the school, conduct filtration experiments, understand the concepts of mixtures and variables, and then design a water filter prototype using simple materials. Cross-subject integration emerges naturally: mathematics for calculating material ratios, language for writing reports, social studies for discussing environmental issues, and ICT for documenting results. With teacher guidance, students not only produce products but also understand the underlying scientific concepts.

Ultimately, primary school teachers who are ready to implement STEM are those who can present learning with clear conceptual objectives, use contextual phenomena as catalysts, guide students in data-driven investigations, and integrate technology to strengthen understanding. Authentic assessment and a culture of reflection are integral to this process, so that STEM learning becomes more than just a slogan, but rather a means of educational transformation. With adequate pedagogical readiness and competency, primary school teachers act as driving forces, ensuring students acquire the critical, creative, analytical, and collaborative thinking skills that are at the heart of 21st-century education.

2. Barriers to STEM Implementation in Elementary Schools

Barriers to implementing STEM education in elementary schools are multidimensional issues interconnected by internal school factors, teacher capacity, and policy support. At the facility level, limited technology and laboratory infrastructure are the most fundamental obstacles, as available equipment often does not function optimally or is not suited to the needs of elementary school-aged children. The lack of flexible space for exploration, the limited availability of consumables, and rigid procurement regulations further exacerbate the situation, leading to project-based learning practices often stalling at the introductory stage without sustainability. This situation demonstrates that nominal access to equipment does not necessarily guarantee its meaningful use in learning activities that should foster creativity and 21st-century skills.

Furthermore, the capacity of PGSD teachers to integrate science, technology, engineering, and mathematics content with an active pedagogical approach remains a major challenge. Most teacher training is one-off and lacks ongoing support, providing neither real-world practice nor intensive mentoring in the form of coaching or professional learning communities. Teachers also struggle to develop a comprehensive TPACK (Integrated Skills for Learning) approach, specifically the ability to integrate content, pedagogy, and technology, particularly in designing authentic assessments that assess both collaborative processes and student work. Another obstacle arises from the safety aspect of children's laboratories, which is rarely a focus of training, leading teachers to opt for simple activities deemed safe but lacking in conceptual exploration. As a result, STEM learning fails to achieve its profound essence, namely developing higher-order thinking skills from an early age.

Resistance to change in innovative learning methods also slows the integration of STEM in elementary schools. A school culture still oriented towards lectures and written exams makes teachers hesitant to try project-based approaches that require flexibility in time, courage to experiment, and tolerance for productive failure. This situation is exacerbated by administrative burdens and the demands of achieving curriculum targets, which tend to push teachers to choose conventional teaching methods that are faster and more administratively secure. In fact, the phenomenon of "innovation fatigue" emerges when too many new programs are introduced without clear structural support. Gender stereotypes also contribute to cultural barriers, such as the assumption that technology is only relevant for male students, which ultimately reduces equitable participation in the classroom.

On the other hand, educational policies that are not yet fully consistent in supporting STEM integration also pose a structural obstacle. Thematic curricula do provide opportunities for integration, but assessments and school performance indicators still tend to be fragmented by subject. As a result, cross-disciplinary projects struggle to gain administrative legitimacy, particularly in terms of time allocation and assessment of learning outcomes. Limited budget flexibility also presents challenges, as schools lack the funds to fund equipment maintenance, procure experimental materials, or establish partnerships with external parties. Furthermore, STEM pilot programs launched by the government or specific institutions often lack ongoing monitoring and evaluation mechanisms, making it difficult to replicate good practices widely.

Geographically, the differences between urban and rural schools reveal distinct patterns of barriers. Urban schools tend to face issues of curriculum overcrowding, limited learning space, and oversized classes, making project management difficult. Meanwhile, rural schools are more hampered by the digital divide, limited access to electricity and internet, and distance from potential partners such as universities or industry. However, rural schools have significant potential to leverage local contexts, such as the natural environment and agricultural activities, as authentic materials for STEM projects. Unfortunately, limited technical support and training prevent this potential from being fully tapped, resulting in underdevelopment of innovations based on local wisdom.

Another often overlooked obstacle is the difficulty in designing STEM assignments that are appropriate for the cognitive developmental level of elementary school children. Without proven examples of learning units, teachers tend to design activities that are either too simple, resulting in poor conceptual understanding, or too complex, making them difficult for students to grasp. Differentiation of learning to meet the needs of diverse students, including those with special needs, is also rarely considered, even though STEM projects require collaboration across diverse roles. Furthermore, time constraints often result in the skipping of crucial stages such as planning, prototyping, and reflection, resulting in the goal of developing critical and creative thinking. This situation emphasizes the need for adaptive curriculum guidance and applicable examples of good practice.

Another obstacle relates to the weak partnership networks and curriculum resources available to teachers. STEM implementation truly requires support from universities, industry, maker communities, and parents, but cross-stakeholder coordination remains suboptimal. Contextual and accessible STEM learning materials in Indonesian are still limited, making it difficult for teachers to find comprehensive modules containing step-by-step guides, assessment rubrics, and safe experimental materials. External device donation programs often only provide equipment without any support, resulting in schools underutilizing the equipment received. Consequently, teachers continue to rely on traditional methods, feeling they lack the resources to develop STEM learning.

Through a literature review, all these barriers can be comprehensively mapped to identify the interrelationships between facilities, teacher capacity, school culture, policies, and differences in geographic context. A systematic review using a thematic coding approach allows for the identification of barriers that can be quickly addressed and those that require long-term intervention. The results of this mapping not only describe the challenges but also help prioritize implementation strategies that are more realistic and contextual. Thus, barriers to STEM implementation in elementary schools can be viewed not simply as obstacles but also as a roadmap for formulating innovative and sustainable solutions to support the quality of learning at the elementary level.

3. Strategies for Strengthening Teacher Competence in Integrating STEM

Strategies for strengthening the competency of primary school teacher educators (PGSD) in integrating STEM require a systematic and multi-layered approach to address the real needs of elementary school classrooms. The initial step can begin with a needs assessment to determine teachers' understanding of STEM content, pedagogical mastery, and technological skills. The results of this mapping will yield a clearer target competency profile. For example, teachers are expected to be able to design cross-subject projects that connect local phenomena with simple data representations and engineering prototypes. With a measurable initial understanding, strengthening strategies can be directed along appropriate learning paths and evaluated continuously (Putri et al., 2024).

The next step is to organize practice-based training that focuses on the cycle of teachers' real-life experiences, from design workshops, microteaching, classroom implementation, and reflection. Training materials should be rooted in phenomena close to students' lives, such as flooding, waste management, or air quality, so that learning feels relevant and contextual. Furthermore, the integration of the engineering design process and an inquiry-based approach needs to be practiced so that teachers are accustomed to facilitating students in finding solutions, rather than simply receiving knowledge (Wi & Zhou, 2025). Reinforcement of training can also be complemented by a micro-credential system in the form of specific skills certificates, which boost teacher motivation and provide formal recognition of their competence.

However, training should not be confined to one-off activities; it must be reinforced with ongoing mentoring mechanisms. Approaches such as coaching and lesson study can provide a platform for teachers to collaboratively design lessons, conduct classroom observations, and reflect on data-driven teaching practices. The presence of teacher learning communities (KKG) that regularly share experiences, teaching tools, and practical challenges is also a crucial pillar in building a collaborative culture. With regular discussion spaces, teachers not only develop individual capacity but also contribute to building a collective and sustainable STEM learning ecosystem.

Furthermore, the use of digital technology is a crucial strategy that cannot be ignored. Technology can be used not only as a presentation tool but also as a means of concept exploration, simulation, data collection, and simple prototyping. For example, teachers can integrate simple sensors, block-based programming applications, and learning management system platforms to support students' project activities and digital portfolios. However, infrastructure limitations in elementary schools must be addressed with low-tech alternatives such as the use of data cards or manual graphs, so that the principle of inclusivity is maintained. With adaptive mastery of technology, teachers can broaden learning horizons without abandoning the realities of the local school context (Hamad et al., 2022).

Partnerships with universities and external ecosystems are also a key strategy in strengthening teacher competency. Through collaboration with LPTK (Institute for Teacher Training and Education), teachers can receive guidance in curriculum design, access laboratories, and attend guest lectures that enrich STEM literacy. The presence of PPL students as near-peer mentors can provide additional support for teachers in implementing project-based learning. Furthermore, the involvement of local industry, maker communities, and local governments can also broaden the relevance of learning, for example by presenting project themes related to resource management or environmental innovation. This collaboration will strengthen teacher networks while providing a more authentic learning experience for students.

In the context of learning, the most relevant strategy for integrating STEM is the implementation of a project-based learning model or Project-Based Learning (PjBL), which prioritizes an interdisciplinary approach. Through PjBL, students are invited to research real phenomena, design solutions, test prototypes, and conduct metacognitive reflection on their work. Elementary school teacher education teachers need to be trained to develop provocative questions, develop authentic assessment rubrics, and ensure that elements of Science, Technology, Engineering, and Mathematics are integrated equally into learning activities. With a structured flow through the stages of design thinking and the 5E cycle, students will engage in more meaningful and in-depth learning experiences.

Evaluation is an integral part of the strategy to strengthen teacher competency. Assessment is directed not only at student achievement but also at the development of teacher competency in integrating STEM in the classroom. Evaluation indicators can include the quality of lesson plans, high-level questioning skills, the ability to orchestrate project activities, and the teacher's success in fostering a collaborative culture in the classroom. For students, assessment is conducted through product and process rubrics, digital portfolios, and evidence-based reasoning skills. This dual evaluation mechanism allows teachers to engage in more in-depth self-reflection while simultaneously monitoring the impact of learning on student development.

Finally, strategies to strengthen PGSD teachers' competencies in STEM integration need to be guided by sustainability principles. Teachers should be encouraged to apply Universal Design for Learning principles to ensure inclusive learning for all students, regardless of their background or abilities. The use of recycled materials and simple equipment can be a creative solution to resource constraints while fostering environmental awareness. Furthermore, teachers' good practices can be documented in portfolios, showcased at local events, and disseminated through the Teachers' Working Group (KKG) forum. With a holistic strategy, from assessment and training to mentoring and technology utilization, external collaboration, and sustainability, PGSD teachers will be better prepared to equip students to face 21st-century challenges through a solid STEM foundation

CONCLUSION

In conclusion, the pedagogical readiness of PGSD teachers is an essential foundation for the successful implementation of STEM education in elementary schools because teachers act as facilitators, guiding students to understand phenomena scientifically and contextually. This readiness encompasses content knowledge, pedagogical skills, technological literacy, and interconnected professional dispositions. Mature teacher competencies enable STEM learning to evolve from simple projects to tools for critical, analytical, creative, and collaborative thinking. The implementation of project-based learning, inquiry, and engineering design requires teachers to provide learning experiences relevant to real life. Authentic assessments that assess both process and product are crucial for ensuring in-depth learning. However, obstacles such as limited facilities, lack of ongoing training, and resistance to change remain real obstacles in the field. Efforts to strengthen teacher readiness must be carried out through practice-based training, lesson study, coaching, and professional learning communities. The use of digital technology and low-tech alternatives is crucial to support inclusive learning. Collaboration with universities, industry, and local communities is also a strategic avenue for expanding relevance and resources. Continuous evaluation of teacher competency and instructional practices is a crucial indicator in mapping development needs and directions. With a systematic strategy, teachers can gain confidence in integrating STEM into thematic curricula. Ultimately, pedagogically prepared primary school teachers will be the driving force behind the transformation of elementary education toward adaptive and sustainable 21st-century learning.

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