International Journal on Education Insight
Vol. 7, No. 2, April 2026, pp. 253-270
e-ISSN: 2722-2691 p-ISSN: 2722-2683 DOI: 10.12928/ijei.v7i2.14956
REVIEW PAPER

Integrating technology into innovative learning environments to support mathematical knowledge, skills, and STEM learning

Rizki Sariningtias [1], Farida Nurhasanah [1,*], Getut Pramesti [1]

[1] Mathematics Education Study Program, Faculty of Teacher Training and Education, Universitas Sebelas Maret, Jl. Ir. Sutami No. 36A, Kentingan, Surakarta, Central Java 57126, Indonesia
*Corresponding author

Abstract
This systematic literature review examines how technology is integrated into Innovative Learning Environments (ILEs) to support mathematical knowledge, skills, and STEM learning. Following the PRISMA guidelines, 22 studies published between 2013 and 2025 were selected from Scopus and Google Scholar. The review addressed six areas: research trends, definitions and characteristics of ILEs, forms of technology integration, types of mathematical knowledge and skills developed, contributions to 21st-century skills, and support for STEM integration. The findings indicate that Learning Management Systems, Virtual Learning Environments, interactive simulations, gamification, and Virtual Reality were among the most frequently reported technologies. Across the reviewed studies, these technologies were associated with the development of conceptual and procedural mathematical knowledge and the 4C skills of critical thinking, creativity, collaboration, and communication. Technology-enhanced ILEs also supported STEM integration through interdisciplinary and project-based activities connecting mathematical concepts with science, technology, and engineering contexts. However, the reported outcomes varied according to pedagogical design, teacher readiness, infrastructure, and local context. This review provides an integrated synthesis of the physical, pedagogical, social, and technological dimensions of ILEs and offers implications for the development of contextual technology- and STEM-integrated mathematics learning.

Keywords: innovative learning environments, mathematical knowledge and skills, STEM integration, systematic literature review, technology integration

How to cite: Sariningtias, R., Nurhasanah, F., & Pramesti, G. (2026). Integrating technology into innovative learning environments to support mathematical knowledge, skills, and STEM learning. *International Journal on Education Insight, 7*(2), 253-270. https://doi.org/10.12928/ijei.v7i2.14956

Article history: Received 13/11/2025, Accepted 17/08/2026, Published 18/08/2026

Correspondence address: Mathematics Education Study Program, Faculty of Teacher Training and Education, Universitas Sebelas Maret, Jl. Ir. Sutami No. 36A, Kentingan, Surakarta, Central Java 57126, Indonesia. E-mail: farida.nurhasanah@staff.uns.ac.id

INTRODUCTION

Mathematics is a fundamental component of education because it develops critical thinking, logical reasoning, and problem-solving skills that are essential for addressing 21st-century challenges (NCTM, 2020). However, mastering mathematics is not only about knowing concepts, but also about how students use that knowledge in real contexts. It is therefore important to distinguish between mathematical knowledge and mathematical skills. Rittle-Johnson and Schneider (2015) assert that mathematical knowledge encompasses an understanding of facts, concepts, procedures, and the relationships among concepts in mathematics. There are three main types: (1) factual knowledge, namely basic knowledge of symbols and terms (for example, knowing that 3×4=12); (2) conceptual knowledge, namely understanding the meaning of and relationships among ideas (for example, understanding what a ratio or function is); and (3) procedural knowledge, namely the ability to apply steps to solve problems systematically (Rittle-

Johnson & Schneider, 2015). This knowledge forms the basis for developing higher-order mathematical thinking skills. Meanwhile, mathematical skills relate to applying that knowledge to reason, model, represent, communicate, and solve problems. Based on the 21st-century skills framework, mathematics learning needs to develop four core competencies, namely *Critical Thinking, Collaboration, Communication,* and *Creativity*.

In Indonesia, achievement in mathematical knowledge and skills remains low. The 2019 TIMSS results show Indonesia ranked 44th out of 58 countries with an average score of 397, below the international average of 500 (Mullis et al., 2020). The 2022 PISA results likewise show that Indonesian students are only able to solve routine problems but struggle with contextual problems requiring modeling and reasoning (OECD, 2019). The 2021 AKM (Minimum Competency Assessment) results confirm that only 46.5% of students reach the minimum numeracy competency. These facts indicate that mathematics learning has not yet optimally developed higher-order thinking skills. One contributing factor is the dominance of conventional, teacher-centered learning methods (*teacher-centred*) that limit student engagement (Freeman et al., 2014).

Various studies demonstrate that innovative, technology-based learning strategies can improve student engagement, conceptual understanding, and critical thinking and communication skills (Liew, 2023; Saputro et al., 2024). In this context, the concept of *Innovative Learning Environments* (ILE) becomes relevant because it offers a holistic approach that combines physical, social, pedagogical, and technological dimensions.

According to OECD (2013), an *Innovative Learning Environment* is “a learning environment that reengineers its core pedagogical elements through strong design, creating innovative learning organizations, and driving 21st-century learning effectiveness based on learning principles.” ILE does not only focus on spatial design but also emphasizes collaboration, flexibility, and technology integration to enhance student engagement (Byers, Imms, & Hartnell-Young, 2018).

Technology is a key element in supporting the function of ILE as an adaptive learning system. According to UNESCO (2023), educational technology is a digital device, service, or process used to enhance learning and support educational goals. Based on its nature, technology is divided into two categories: (1) digital technology, such as computers, laptops, tablets, *Learning Management System* (LMS), *Virtual Learning Environment* (VLE), simulations, gamification, and *Virtual Reality* (VR) (OECD, 2023); and (2) non-digital technology, such as whiteboards, concrete manipulatives, number cards, *flipchart,* or posters (Bolaño-Truyol et al., 2023). Both types of technology complement one another in facilitating active, contextual, and collaborative learning. The integration of both forms of technology within ILE has been shown to strengthen both mathematical knowledge and skills. Applying the *Technological Pedagogical and Content Knowledge* (TPACK) framework with interactive software enhances students' conceptual understanding and procedural skills (Muhtadi et al., 2018). Liu et al. (2009) add that the success of technology-based learning depends on teacher support and the flexibility of learning resources. However, the effectiveness of ILE is also strongly influenced by the social and cultural context and the readiness of school infrastructure (Alakoski et al., 2024).

Although the implementation of ILE has been widely developed across countries, there remains a research gap concerning how digital and non-digital technologies are effectively integrated to support the development of mathematical knowledge and skills. Most previous studies have only highlighted physical or pedagogical space design without explaining how technology acts as a catalyst for meaningful mathematics learning (Blackmore et al., 2011). Inconsistency has also been found in how previous studies define ILE: some focus on the physical design of classroom space, while others emphasize pedagogical or social dimensions, so that no integrated, widely agreed-upon conceptual framework yet exists. In addition, most studies have been conducted in developed countries with adequate infrastructure, so their findings may not necessarily be relevant to developing-country contexts. Another unresolved issue is the lack of empirical evidence on how technology integration specifically shapes different types of mathematical knowledge, including factual, conceptual, and procedural knowledge within ILE. Furthermore, the potential of ILE to support cross-disciplinary learning such as *Science, Technology, Engineering, and Mathematics* (STEM) has also not been widely studied (Grivokostopoulou & Perikos, 2016). In fact, STEM integration within ILE can bridge theory and practice through problem-based projects that foster creativity, collaboration, and authentic problem solving (Akinpelu & Alamu, 2023).

This gap becomes even more apparent when this study is compared with several previous reviews addressing related fields. Vijapur et al. (2021) focused their review on interior design and environmental quality in *flexible learning environments* in primary schools, while Kariippanon et al. (2021) examined the relationship between flexible learning spaces and movement behavior, engagement, interaction, and educational outcomes among adolescent students. In the higher education context, Christou et al. (2023) mapped physical, virtual, and hybrid learning spaces, emphasizing the benefits, challenges, and design guidelines for learning spaces. Meanwhile, Hidayat and Firmanti (2024) reviewed technology integration in mathematics education but did not specifically analyze technology as part of the Innovative Learning Environments dimensions, which include physical, pedagogical, social, and technological aspects. Thus, previous reviews have tended to discuss learning-space design, educational outcomes, or technology integration separately. Studies that simultaneously synthesize the relationships among the ILE dimensions, digital and non-digital technology integration, the development of mathematical knowledge and skills, 21st-century skills, and STEM integration in the context of mathematics education remain limited. This study fills that gap by using social constructivism and TPACK as frameworks for interpreting the relationships among technology, pedagogy, social interaction, and mathematics learning.

Based on this gap, this study seeks to answer six main research questions, namely:

(1) How have research trends related to *Innovative Learning Environment* (ILE) developed between 2013 and 2025?
(2) How do studies define and characterize ILE in the context of mathematics learning?
(3) What technologies are used, and how are they integrated within ILE in mathematics learning?
(4) What types of mathematical knowledge and skills are developed through technology integration within ILE?
(5) How does technology integration within ILE contribute to the development of 21st-century mathematics skills?
(6) How do the characteristics of technology-based ILE support the integration of STEM learning in the context of mathematics?

In line with these questions, the aim of this study is to analyze the integration of technology within *Innovative Learning Environments* (ILE) to support the development of mathematical knowledge and skills, and to explore how the characteristics of technology-based ILE can accommodate STEM learning in the context of mathematics education. Unlike previous reviews, the novelty of this study lies in its simultaneous synthesis of the relationships among the four ILE dimensions physical, pedagogical, social, and technological with digital and non-digital technology integration, the development of mathematical knowledge and skills, 21st-century skills, and STEM integration. This synthesis is then interpreted through the lens of social constructivism and the TPACK framework to produce a more integrated understanding of technology's role within ILE in the context of mathematics education.

This study is grounded in two complementary theoretical frameworks. First, Vygotsky's (1978) social constructivism theory emphasizes that knowledge is constructed through social interaction and the use of mediating tools, including technology, within the Zone of Proximal

Development (ZPD). Within the ILE context, technology serves as a mediating tool that facilitates collaboration, scaffolding, and the active construction of mathematical knowledge. This theory provides a basis for analyzing how technology-based ILE fosters productive social interaction and meaningful learning. Second, the TPACK (Technological Pedagogical and Content Knowledge) framework developed by Mishra and Koehler (2006) emphasizes that the effectiveness of technology-based teaching depends on the harmonious integration of content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK). In this study, TPACK is used as an analytical lens to evaluate how the technology integration in the reviewed articles reflects a balance among mathematical content, pedagogical approach, and appropriate technology use. Together, these two frameworks form the conceptual foundation for analyzing and interpreting the findings from the 22 articles reviewed. Through a *systematic literature review* (SLR), this study is expected to make a conceptual contribution in the form of a comprehensive mapping of trends, forms of technology integration, and the role of ILE in strengthening 21st-century mathematical knowledge and skills. The results are expected to serve as a basis for developing pedagogical innovations and mathematics education policies that are more contextual and sustainable in the digital era.

RESEARCH METHOD

This study uses a systematic literature review (SLR) approach as a type of qualitative research that focuses on the structured analysis and synthesis of previous studies' results. This method was chosen to obtain a comprehensive understanding of how technology is integrated within *Innovative Learning Environments* (ILE) to support the development of mathematical knowledge and skills. The review followed the PRISMA guidelines and adapted the four-stage framework described by Dixon-Woods, as cited in El Islami et al. (2022), comprising identification, screening, eligibility assessment, and data synthesis. At the identification stage, literature was collected from two main databases, Google Scholar and Scopus, covering publications from 2013–2025.

The next step was to search for articles. The search process was carried out using the *Publish or Perish* version 8 software, with two main keyword combinations: *"Innovative Learning Environment"* in the title field and *"Innovative Learning Environment AND Mathematics"* in the keyword field. The final search was conducted on 18 May 2025. The initial search results can be seen in Table 1.

Table 1. Initial search results

Search Term	Database	Search Limitation	Results
Innovative learning environment (in title)	Google Schoolar	Published 2013–2025	73
Innovative learning environment AND mathematics (in keywords)	Scopus	Published 2013–2025	8

The initial search yielded 81 articles, consisting of 73 articles from Google Scholar and eight articles from Scopus. After five duplicate articles were removed, 76 unique articles remained. Next, title and abstract screening was carried out by applying inclusion and exclusion criteria to ensure the articles' relevance to the study's focus. Articles included had to meet the following criteria:

(1) discussed Innovative Learning Environments in the context of mathematics learning or technology integration within ILEs;
(2) reported empirical research using qualitative, quantitative, mixed-methods, design-based research, or research and development approaches;
(3) were published between 2013 and 2025;
(4) were published in journals or conference proceedings indexed in Scopus or Google Scholar;
(5) were available in full text.

Articles that were opinion pieces, theoretical reviews, policy reports, or publications not relevant to the focus on ILE and technology were excluded. Each selected article had to answer at least one of the six research questions that had been formulated. During the title and abstract screening stage, 36 articles were excluded for not meeting the study's focus and criteria, leaving 40 articles to proceed to the full-text retrieval stage. Five articles could not be fully obtained, leaving 35 articles to be assessed for eligibility through full-text review. At that stage, 13 articles were excluded, comprising nine articles that did not meet publication or indexing criteria, three articles outside the scope of educational or mathematical ILE, and one article that was a review or non-empirical publication. Consequently, 22 articles 18 from Google Scholar and four from Scopus proceeded to the quality assessment and synthesis stage.

To assess the methodological quality of each article, this study used a quality assessment rubric adapted from Mullet (2016). The rubric comprises seven criteria: (1) research objectives and purposes, (2) literature review, (3) theoretical or conceptual framework, (4) participants, (5) methods, (6) results and conclusions, and (7) research significance. Each criterion was rated on a four-point scale: 1 (*does not meet the standard*), 2 (*nearly meets the standard*), 3 (*meets the standard*), and 4 (*exceeds the standard*). A complete description of each criterion and its assessment indicators is presented in Table 2.

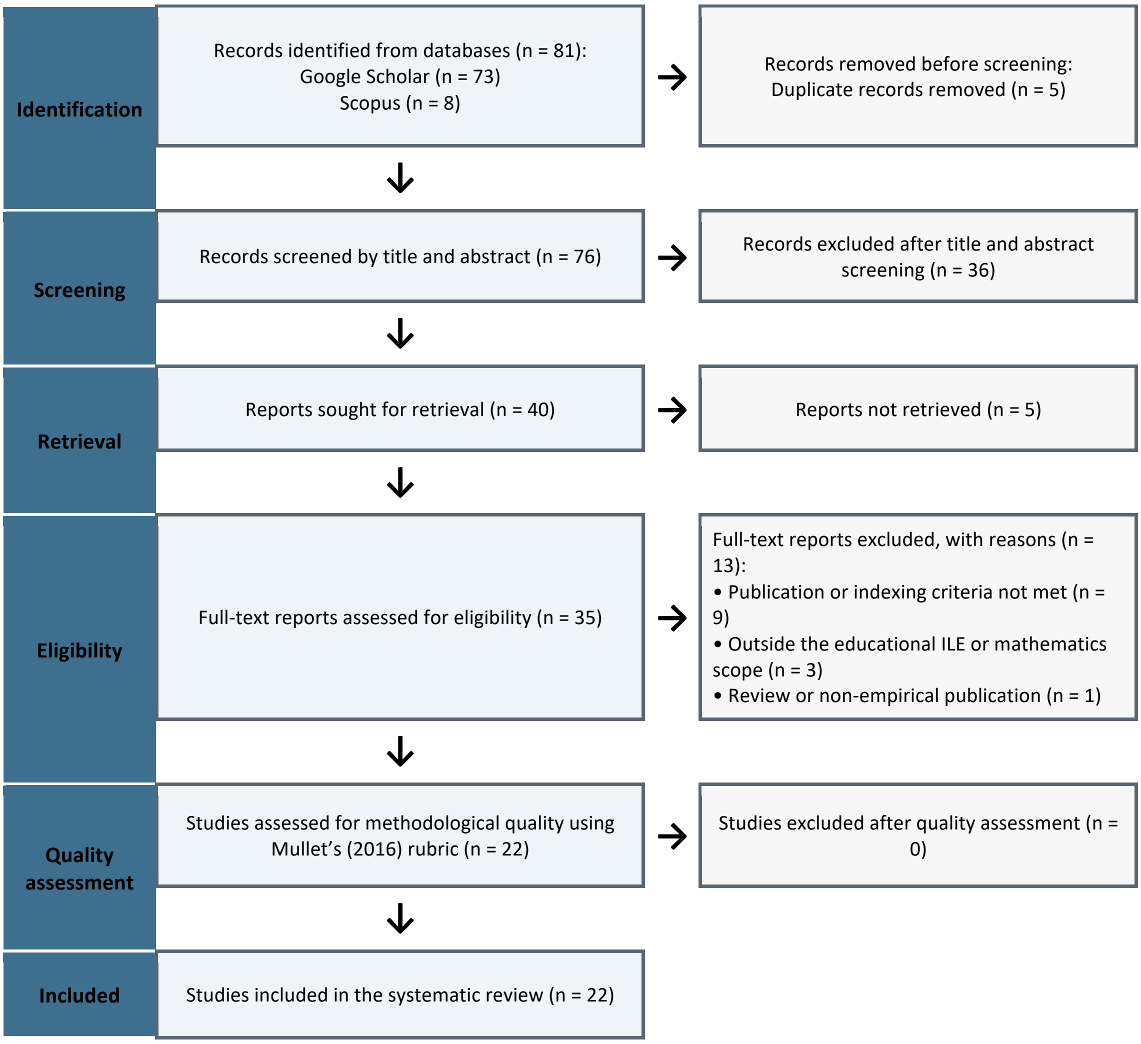

Figure 1. PRISMA flow diagram of the study identification and selection process

Table 2. Mullet's (2016) quality assessment rubric

Criterion	4 Exceeds Standard	3 Meets Standard	2 Nearly Meets Standard	1 Does Not Meet Standard
I. Objectives and purposes	Clearly articulated problem, objective, rationale, research questions.	Adequately articulated.	Poorly articulated.	Incomplete.
II. Review of literature	Critically examines state of the field. Clearly situates the topic within the broader field. Makes compelling connection to past work. Discusses and resolves ambiguities in definitions. Synthesizes and evaluates ideas; offers new perspectives.	Discusses what has and has not been done. Situates topic within the broader field. Makes connections to past work. Defines key vocabulary. Synthesizes and evaluates ideas.	Minimally discusses what has and has not been done. Vaguely discusses broader field. Makes few connections to past work. Lacks synthesis across literature. Minimal evaluation of ideas.	Fails to discuss what has and has not been done. Topic not situated within broader literature. No connections to past work.
III. Theoretical or conceptual frameworks	Clearly articulated and described in detail. Frameworks align with study purposes.	Articulated; aligns with study purposes.	Implied or described in vague terms, or fails to align with purposes.	Absent.
IV. Participants	Detailed, contextual description of population, sample and sampling procedures.	Detailed description of population, sample and procedures.	Basic description of sample and procedure elements.	Incomplete.
V. Methods	Instruments and their administration described in detail. Evidence for validity and reliability. Documented best research practices. Potential bias considered.	Instruments and their administration described. Evidence for validity or reliability. Some evidence of best research practices. Potential bias considered.	Instruments described. Incomplete evidence of validity or reliability. Questionable research practices.	Incomplete.
VI. Results and conclusion	Detailed results. Exceptional use of data displays. Discussion clearly connects findings to past work. Proposes future directions for research. Conclusions clearly address the problem or questions.	Complete results. Sufficient use of data displays. Discussion connects findings to past work. Conclusions address the problems or questions.	Basic results. Insufficient use of data displays. Discussion fails to connect findings to past work. Conclusions summarize findings.	Incomplete.
Significance	Clearly and convincingly articulates scholarly and practical significance of the study.	Articulates scholarly and practical significance of the study.	Articulates scholarly or practical significance, but is neither clear nor convincing.	Not articulated.

The total score for each article ranged from 7 to 28, and articles with a total score ≤14 were excluded from the review. The screening, eligibility assessment, and quality assessment processes were carried out using criteria established prior to the analysis. The first author reviewed the titles, abstracts, and full texts and assigned quality scores based on the Mullet (2016) rubric. The inclusion and exclusion decisions and quality assessment results were then checked by the second author to ensure consistent application of the criteria. Where assessments differed, the two authors discussed the article in question by referring back to the inclusion criteria, exclusion criteria, and rubric indicators until agreement was reached. The third author provided additional input when agreement had not yet been reached. In addition, the reasons for exclusion at the full-text review stage were recorded to maintain the transparency of the selection process. These procedures were applied to reduce potential selection bias and subjectivity in the quality assessment of the articles. The assessment results show that the quality scores of the 22 articles meeting the criteria ranged from 18 to 28, with a mean of 24.59 and a median of 25. Nine articles achieved the maximum score of 28, and no articles scored at or below the exclusion threshold. Accordingly, all 22 articles met the methodological eligibility standard and were retained for the synthesis stage. The detailed scores for each article are presented in Table 3. The complete identification, screening, eligibility assessment, quality assessment, and inclusion process is presented in Figure 1.

Table 3. Quality assessment scores of the included studies based on Mullet (2016)

No.	Study	OP [a]	RL [b]	TF [c]	PA [d]	ME [e]	RC [f]	SI [g]	Total
1	Alakoski et al. (2024)	4	4	4	3	3	4	4	26
2	Byers (2018)	3	3	2	4	4	3	3	23
3	Alakoski et al. (2025)	4	3	3	3	3	4	3	23
4	Everatt et al. (2019)	3	2	2	3	3	3	2	18
5	Alghanmi (2014)	3	2	3	3	3	3	2	19
6	Półjanowicz et al. (2014)	3	3	3	3	3	4	3	22
7	Grivokostopoulou and Perikos (2016)	4	4	4	4	4	4	4	28
8	Magen-Nagar and Steinberger (2017)	4	3	3	4	3	4	3	24
9	Byers et al. (2018)	4	4	4	4	4	4	4	28
10	Lineses and Aguilar (2019)	3	3	3	3	3	3	3	21
11	Campbell (2020)	4	4	4	4	4	4	4	28
12	Arnesen et al. (2021)	4	4	4	4	4	4	4	28
13	Kampinga et al. (2021)	4	3	3	4	4	4	4	26
14	Glassner (2022)	4	4	4	4	4	4	4	28
15	Cavadas and Correia (2022)	3	3	3	3	3	3	3	21
16	Liew et al. (2023)	4	3	3	3	3	4	3	23
17	Akinpelu and Alamu (2023)	4	4	4	4	4	4	4	28
18	Bhat et al. (2023)	3	3	3	3	3	4	3	22
19	Saastamoinen et al. (2023)	4	4	4	4	4	4	4	28
20	Zhao (2023)	3	3	3	3	3	3	3	21
21	Saputro et al. (2024)	4	4	4	4	4	4	4	28
22	Könings and Seidel (2025)	4	4	4	4	4	4	4	28

[a] OP = objectives and purposes;
[b] RL = review of literature;
[c] TF = theoretical or conceptual framework;
[d] PA = participants;
[e] ME = methods;
[f] RC = results and conclusions;
[g] SI = significance.

Each criterion was rated from 1 (does not meet the standard) to 4 (exceeds the standard), resulting in a possible total score ranging from 7 to 28. Studies with a total score of 14 or lower were excluded from the review.

The data synthesis stage was carried out by organizing the selected articles according to six focus areas, namely research trends, ILE definitions and characteristics, forms of technology integration, the types of mathematical knowledge and skills developed, technology's contribution to 21st-century skills, and ILE's support for STEM learning. The analysis was conducted descriptively and thematically to identify patterns, similarities, and conceptual contributions across studies.

In addition to identifying patterns and similarities, the synthesis process also considered differences and inconsistencies in findings across studies. When the reviewed studies reported differing results regarding technology integration or ILE characteristics, these findings were compared based on country context, education level, participant characteristics, research design, technology type, pedagogical approach, implementation duration, and the methodological quality of the article. Differing findings were not simply merged into a single general conclusion but were analyzed to identify contextual factors that might explain the variation in results. This synthesis therefore not only describes general tendencies but also highlights the conditions that can influence the success of technology-based ILE implementation

In this analysis process, two theoretical frameworks were used to guide interpretation. Vygotsky's (1978) social constructivism theory was used to identify and interpret findings related to the role of social interaction and technology as mediating tools in constructing mathematical knowledge. Each article was examined from the perspective of whether and how the technology used functioned as scaffolding to support students' learning within the ZPD. Meanwhile, the TPACK framework (Mishra & Koehler, 2006) was used as a categorization framework to evaluate the balance among mathematical content, pedagogical approach, and technology applied in each study. Articles demonstrating strong integration among the three TPACK components were categorized as examples of effective ILE practice. In short, this method was designed to allow readers to adapt the research process directly to different contexts while maintaining the principles of transparency, replicability, and objectivity of a systematic review.

RESULTS AND DISCUSSION

This section presents the results and discussion of the 22 articles, analyzed descriptively to identify patterns, trends, subjects, geographical distribution, research types, ILE characteristics, and the forms and contributions of technology to the development of knowledge, mathematical skills, and STEM integration. The discussion interprets these findings to answer the six established research questions. The results of the studies selected for this systematic review are presented in Table 3. Research trends in ILE over the past 13 years are presented in Figure 3.

Figure 2. Research trends

The earliest included study was published in 2014, and the number of publications peaked in 2023 with five studies, likely reflecting the acceleration of digital education transformation following the COVID-19 pandemic (Liew, 2023). Since then, publications have remained stable at around two articles per year through 2025. Overall, 63% of studies focused on technology integration, while the remainder highlighted spatial design or social-pedagogical dynamics.

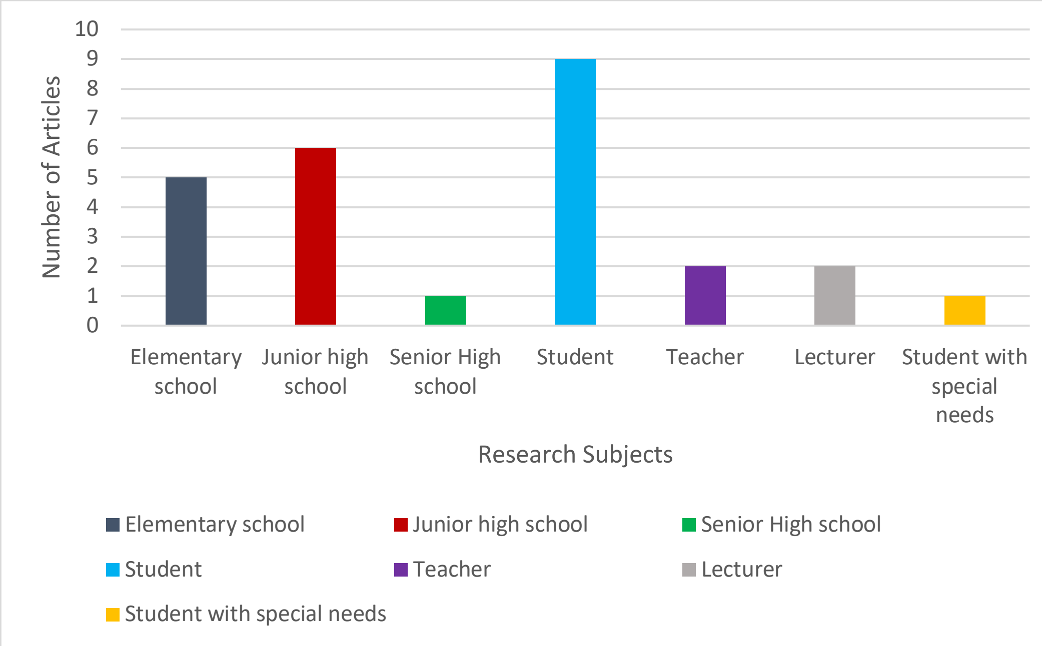

Figure 3. Research subject

This finding confirms that the role of technology has become a dominant component in the development of modern ILE, in line with the acceleration of global education digitalization following the pandemic.

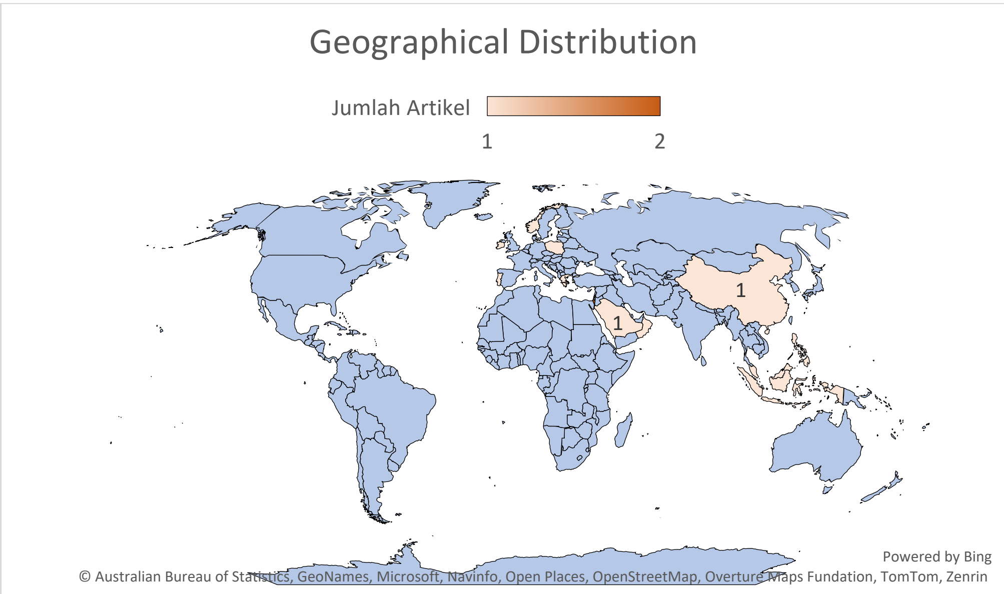

Figure 4. The geographical representation of studies by countries (edited by the authors from 22 selected articles, 2025; basemap: © Australian Bureau of Statistics, GeoNames, Microsoft, OpenStreetMap contributors, TomTom, and ZENRIN)

In terms of research subjects, Figure 3 reveals a dominance of studies based in higher education, with most studies focusing on higher education (universities), followed by junior secondary and elementary levels. This pattern indicates that the implementation of technology-based ILE is more readily applied in higher education institutions, which have more adequate infrastructure. In contrast, research at the senior secondary level and involving teachers and students with special needs remains very limited, indicating that ILE adoption in primary and secondary education has not been evenly distributed and represents a research gap that needs to be addressed promptly.

The geographical distribution of the studies, as shown in Figure 4, reveals a dominance of developed countries, particularly Finland, Australia, and Israel. Asian countries such as Malaysia, Indonesia, and the Philippines have also begun adapting ILE implementation to local contexts, while no publications from Africa were found. This uneven distribution indicates a significant research gap: findings from developed countries cannot necessarily be generalized to developing-country contexts with different digital infrastructure limitations. This pattern underscores the importance of expanding ILE research to more geographically and socioeconomically diverse contexts (Ertmer & Ottenbreit-Leftwich, 2010).

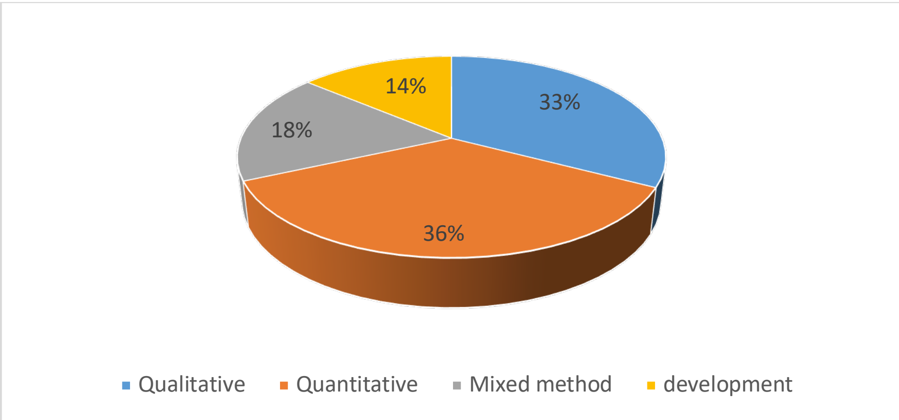

Figure 5. Distribution of Research Types

In terms of research type, Figure 5 shows that quantitative approaches predominate (36%), followed by qualitative and *mixed-method*. Quantitative approaches are widely used to measure the effect of technology on learning outcomes and student skills. In addition, the analysis of ILE definitions and characteristics reveals broad contextual variation, as shown in Table 4.

Table 4. Characteristics of ILEs by country

Dimension	Characteristics	Example Studies (Countries)
Physical	Flexible spaces, innovative environmental design, collaborative zones, co-teaching areas, breakout spaces	Finland (Alakoski et al., 2025), Australia, Scotland, New Zealand, Norway
Technological	Digital integration (VLE, VR, gamification, LMS, multimedia, digital learning platforms)	Ireland, Oman, Philippines, Indonesia, Greece, Malaysia, Poland, USA
Pedagogical	Constructivism, active learning, heutagogy, student-centered learning, agency, active interaction	Israel, Australia, Norway, Portugal, Netherlands, China, Finland (mathematics)
Social	Collaboration, interaction, learning autonomy, student agency, learning communities	Norway, Netherlands, China, Finland (mathematics), Israel, Oman

Some studies emphasize physical and spatial design aspects, such as flexible learning spaces (Saastamoinen et al., 2023), whereas others highlight pedagogical and social dimensions involving collaboration and student agency (Magen-Nagar & Steinberger, 2017). ILE generally encompasses four main dimensions: physical, pedagogical, social, and technological (Byers, Imms, & Hartnell-Young, 2018). A variety of technology forms have been applied within ILE, as summarized in Table 5. The findings show that LMS and VLE predominate as the main platforms facilitating both synchronous and asynchronous learning, followed by interactive simulations and gamification, which serve to make abstract mathematical concepts concrete. Immersive technologies such as VR are still used to a limited extent, generally in higher-education-based studies with adequate infrastructure support. These differing usage patterns reflect variation in technology readiness across contexts, while also confirming that no single technology is universally the most effective; rather, it is a combination of technologies tailored to pedagogical goals and learner characteristics that yields the best impact.

Table 5. Types of digital technologies and forms of integration

Technology Category	Example Applications	Forms of Integration
Digital Technologies	LMS/VLE (Blackboard, Brightspace)	Online discussions, quizzes, e-portfolios, project-based learning
	Virtual Reality (OpenSim, VR goggles)	Immersive learning (e.g., 3D geometry)
	Gamification (KALI App, MOOC 4D)	Game-based learning to enhance motivation
	Online collaboration tools (Zoom, Classkick, social media)	Remote learning and real-time collaboration
	Simulations (ADALM1000, PhET, GeoGebra)	Virtual experiments or mathematical modeling
	Interactive digital devices (laptops, tablets, interactive screens)	App-based activities and interactive presentations
Non-Digital Technologies	Concrete manipulatives (geoboard, tangram, algebra tiles)	Representation and exploration of geometry and algebra concepts
	Printed visuals (posters, concept cards, flipcharts)	Concept explanation, gallery walk, reflection
	Measuring tools (ruler, compass, protractor, coordinate board)	Geometric measurement and manual modeling
	Physical whiteboards or magnetic boards	Demonstrations, group discussions, worked examples

The digital platforms most widely used in this study include *Learning Management System* (LMS), *Virtual Learning Environment* (VLE), *Virtual Reality* (VR), interactive simulations, and gamification (Kampinga et al., 2021). LMS and VLE are used for collaboration and formative assessment, while VR and simulations support the visualization of abstract concepts. Gamification, meanwhile, has been shown to increase learning motivation (Bhat et al., 2023). Furthermore, the mathematical knowledge developed within ILEs can be categorized as factual, conceptual, and procedural knowledge, as summarized in Table 6. Based on the analysis of the 22 articles, conceptual knowledge is most often developed through digital simulation and visualization for example, GeoGebra for understanding geometric and functional concepts. Procedural knowledge is reinforced through gamification-based exercises and collaborative projects, while factual knowledge is built through interactive digital quizzes on LMS platforms. Studies with more favorable reported outcomes generally integrate all three types of knowledge simultaneously through a project-based learning approach, rather than targeting a single type of knowledge separately (Rittle-Johnson & Schneider, 2015).

Table 6. Types of mathematical knowledge in technology-based Innovative Learning Environments (ILE)

Knowledge Category	General Description	Examples of Implementation/Activities in ILE
Factual Knowledge	Understanding symbols, terminology, definitions, and mathematical facts that serve as the foundation for mathematical thinking.	Identifying symbols and notations using LMS; interactive apps for recognizing basic algebraic and geometric elements; digital quizzes in Classkick and Brightspace.
Conceptual Knowledge	Understanding relationships among mathematical ideas, principles, theorems, and conceptual representations explaining why procedures work.	Exploring geometry and functions through simulations and VR; visualizing statistical concepts with GeoGebra and PhET; collaborative discussions on calculus and probability concepts.
Procedural Knowledge	Applying algorithms, rules, and problem-solving steps systematically and efficiently.	Project-based problem-solving; using digital devices such as ADALM1000 for algebraic experiments and measurement; gamified exercises via MOOC 4D.

A number of studies specifically highlight the role of technology-based ILE in supporting STEM integration. As shown in Table 7, ILE facilitates STEM integration primarily through two mechanisms: (1) cross-disciplinary project-based learning, in which students solve authentic problems involving mathematics, science, and technology simultaneously; and (2) the use of simulations and VR that connect abstract mathematical concepts with real-world applications in science and engineering. As a concrete example, studies using robotics within ILE successfully connected programming (technology), physics principles (science), and mathematical modeling (mathematics) within a single integrated activity. This finding confirms that ILE is not merely a learning space but an ecosystem that actively drives cross-disciplinary STEM knowledge transfer.

Table 7. Relationship between ILE dimensions and STEM components

ILE Dimension	Analytical Focus	Connection to STEM Components	Example Studies
Physical	Flexible spaces enabling project-based, experimental, and cross-disciplinary learning.	Supports the Engineering Design Process and collaborative inquiry in STEM projects.	Byers et al. (2018); Campbell (2020)
Technological	Digital technologies integrating science, technology, and mathematics content (VR, simulations, LMS, gamification).	Provides authentic STEM experiences through simulations, virtual labs, and mathematical modeling.	Grivokostopoulou & Perikos (2016); Akinpelu (2023); Saputro (2024)
Pedagogical	Constructivist, project-based, and heutagogical learning approaches.	Facilitates the integration of STEM content with a focus on real-world problem solving.	Liew (2023); Kampinga et al. (2021)
Social	Cross-disciplinary collaboration through digital forums, team projects, and learning communities.	Develops teamwork and communication as cross-cutting STEM competencies.	Alakoski (2025); Lineses & Aguilar (2019)

Flexible spaces enable cross-disciplinary project-based activities, while digital technologies such as simulations, LMS, and VR facilitate authentic experiences based on virtual experimentation and the *engineering design process* (Akinpelu & Alamu, 2023). The synthesis shows that technology integration within ILE strengthens both mathematical knowledge and skills. Conceptual and procedural knowledge improve through interactive visualization and technology-based exercises, while reflective skills develop through online collaboration (Arnesen et al., 2021). Meanwhile, the 21st-century skills most prominently developed are *critical thinking*, *collaboration*, *communication*, and *creativity* (4C), supported by different technologies. Specifically, VR and immersive simulation were frequently reported to support in developing critical thinking and creativity through independent exploration within virtual environments, while LMS and online collaboration platforms such as Zoom and Classkick are more effective in fostering collaboration and communication. This finding aligns with the TPACK perspective (Mishra & Koehler, 2006), which holds that the effectiveness of technology in developing 21st-century skills depends heavily on the alignment among technology choice, pedagogical approach, and the targeted learning content objectives. A comprehensive summary of the relationship among technology, 4C skills, and ILE dimensions is presented in Table 8.

Table 8. 21st-Century Skills and Types of Technology

4C Skills	Types of Technology	Example Applications	Empirical Evidence	References
Critical Thinking	Simulations & VR	OpenSim, ADALM1000	Analytical reasoning in STEM simulations	Grivokostopoulou et al. (2016)
Creativity	Gamification & Interactive Design	KALI App, MOOC 4D	Development of creative solutions through game-based learning	Bhat et al. (2023); Utomo (2024)
Collaboration	LMS/VLE & Online Discussion Forums	Brightspace, Classkick	Collaborative mathematics projects among students and teachers	Kampinga et al. (2021)
Communication	Social Media & VR Avatars	Zoom, VR Chatrooms	Discussion of mathematical concepts via avatars and online chats	Campbell (2020)

Research on ILE shows significant growth over the past decade, reflecting increased attention to learning-space innovation and digital technology integration. The publication peak in 2023 indicates an academic response to the challenges of online learning during the pandemic. However, this still-unstable trend suggests that ILE remains a developing topic requiring a more consistent theoretical framework. Conceptually, ILE is defined as a learning system that combines flexible physical space, collaborative social interaction, active pedagogical approaches, and the use of digital technology. These characteristics are multidimensional and interrelated: flexible space facilitates project-based learning; a constructivist approach fosters learner autonomy; and technology integration expands access and fosters *student agency*. (Byers, Imms, & Hartnell-young, 2018). ILE is thus not merely a spatial innovation, but a comprehensive transformation in teaching and learning practice.

Digital technology predominates within ILE, including LMS, VLE, VR, gamification, and online collaboration tools such as Zoom and Classkick (Kampinga et al., 2021). Both of these web-based platforms strengthen collaboration and communication among students, while VR and simulations facilitate spatial understanding and geometric concepts (Grivokostopoulou & Perikos, 2016). These two web-based platforms strengthen collaboration and communication among students, while VR and simulations facilitate spatial understanding and geometric concepts . Non-digital technology such as concrete manipulatives is still used in contexts with infrastructure limitations (Bolaño-Truyol et al., 2023). This variation shows that the success of technology integration depends on teacher readiness, policy support, and the sociocultural context of the school .

ILE strengthens conceptual, procedural, and reflective knowledge through a combination of digital visualization and project-based learning . Overall, these findings reinforce the argument that effective ILE integrates mathematical knowledge and skills holistically, rather than treating them as two separate domains. From Vygotsky's (1978) perspective, technology within ILE functions as a mediating tool that facilitates scaffolding and productive social interaction, enabling students to progress beyond their initial abilities within the Zone of Proximal Development (ZPD). From the TPACK perspective (Mishra & Koehler, 2006), the studies with the best outcomes are those that successfully balance mathematical content, active pedagogical approaches, and appropriate technology rather than simply adding technology to conventional instruction.

Technology integration within ILE fosters the development of 4C skills, namely *critical thinking, creativity, collaboration,* and *communication*. Simulations and VR are most effective in fostering *critical thinking* and *creativity*, while online collaboration platforms such as LMS strengthen *collaboration* and *communication* through digital projects and forums. This finding reinforces the view that technological diversity creates synergy among complementary 21st-century skills. ILE has proven to be an effective framework for integrating STEM learning. Flexible spaces support the *engineering design process* and *collaborative inquiry*, while digital technologies such as VR and simulations deliver *authentic STEM experiences* that connect mathematics, science, and technology concepts. A *project-based learning* approach within ILE also strengthens cross-disciplinary collaboration and students' creative thinking skills (Akinpelu & Alamu, 2023). ILE thus functions as a conceptual bridge between mathematical theory and cross-field application, while enhancing the relevance of learning to 21st-century needs.

Overall, the findings of this study confirm that the effectiveness of ILE is determined not only by the technology used, but also by pedagogical innovation, a collaborative culture, and school infrastructure readiness. This reinforces the notion that the implementation of technology-integrated innovative learning environments must be tailored to local contexts and supported by ongoing teacher training. A limitation of this study lies in its scope, which remains limited to open-access publications and does not cover all non-English-language literature. Future research is therefore recommended to broaden the range of literature sources and to develop a contextual, empirical STEM-based ILE model for mathematics education in developing countries.

CONCLUSION

This systematic review makes three main contributions. First, conceptually, this study comprehensively maps the trends, forms of technology integration, and characteristics of ILE in mathematics learning over the past 13 years (2013–2025).

The reviewed studies characterize ILEs not merely as innovations in physical space, but as multidimensional learning environments combining physical, pedagogical, social, and technological elements. Second, theoretically, these findings reinforce the relevance of Vygotsky's (1978) social constructivism theory: technology within ILE functions as a mediating tool that facilitates scaffolding and the construction of mathematical knowledge through social interaction. The TPACK perspective further confirms that effective technology integration depends on the balance among content, pedagogy, and technology, rather than on technology use alone. Third, practically, this study shows that technology-based ILE is able to develop three types of mathematical knowledge (factual, conceptual, procedural), 4C skills (critical thinking, creativity, collaboration, communication), and support STEM integration through cross-disciplinary project-based learning.

The success of ILE implementation is determined not by technology alone, but by pedagogical innovation, a collaborative culture, and infrastructure readiness tailored to local contexts. Future research is therefore recommended to expand its scope to more geographical contexts and primary–secondary education levels, and to develop a contextual, empirical STEM-based ILE model. Education practitioners and policymakers need to prioritize ongoing teacher training and the strengthening of digital infrastructure so that ILE can become a genuine bridge between theory, practice, and the educational needs of the 21st century.

ACKNOWLEDGEMENT

The authors would like to thank Universitas Sebelas Maret (UNS) for the academic support and facilities provided during this research. Thanks are also extended to all supervising lecturers and colleagues who provided valuable input in the preparation and refinement of this article. In addition, appreciation is extended to the researchers whose work served as the primary sources for this systematic review. The authors hope that the results of this study can make a real contribution to the development of technology-based mathematics learning practices and educational innovation in Indonesia.

DECLARATION

Author contribution

All authors contribute in the research and/or writing the paper, and approved the final manuscript.

Rizki Sariningtias	Conceptualizing the research idea, leading the investigation, setting up the methodology, and writing the first draft.
Farida Nurhasanah	Assisting the investigation, reviewing the validity of the methodology, analyzing the data, and communicating with editorial board.
Getut Pramesti	Assisting the investigation, reviewing the paper, and enriching the data analysis.

Funding

This research did not receive any funding.

Conflict of interest

All authors declare that they have no competing interests.

Ethics declaration

This study analyzed publicly available published literature and did not involve human participants, animals, or identifiable personal data. Therefore, ethical approval and informed consent were not required.

The use of artificial intelligence

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) for English translation, language editing, and improving the clarity and organization of the manuscript. The authors subsequently reviewed, verified, and revised all AI-assisted content and take full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

Additional information

Not available.

REFERENCES

Akinpelu, O. F., & Alamu, O. J. (2023). Integration of STEM education through project-based learning in digital classrooms. *Journal of Science Education and Technology, 32*(4), 541–556. https://doi.org/10.1007/s10956-023-10012-9

Alakoski, R., Laine, A., & Hannula, M. S. (2024). Teaching mathematics in innovative learning environments. The entangled tensions between the learning environment and pedagogy. *European Journal of Education, 59*, e12661. https://doi.org/10.1111/ejed.12661

Alakoski, R., Laine, A., & Hannula, M. S. (2025). Interaction and collective emotional climate in innovative learning environments in mathematics lessons: A third- and fourth-grade students' perspective. *Learning Environments Research, 28*, 81–102. https://doi.org/10.1007/s10984-025-09530-7

Alghanmi, S. (2014). Investigating the interpersonal and contextual factors governing Saudi lecturers' motivation in creating an innovative Web 2.0-based blended learning environment. *The Turkish Online Journal of Educational Technology, 13*(3), 96–109.

Arnesen, T., Arnesen, T. E., & Elstad, E. (2021). Exploring students' explanations for off-task practices in an innovative learning environment (ILE) using a typology of agency as a theoretical framework. *Pedagogy, Culture & Society, 29*(4), 651–668. https://doi.org/10.1080/14681366.2020.1777461

Bhat, A., Sharma, P., & Wani, M. (2023). Gamification for enhancing students' motivation in mathematics learning. *Education and Information Technologies, 28*(2), 1841–1860. https://doi.org/10.1007/s10639-022-11072-5

Blackmore, J., Bateman, D., O'Mara, J., & Loughlin, J. (2011). *Research into the connection between built learning spaces and student outcomes*. Department of Education and Early Childhood Development. https://www.education.vic.gov.au/Documents/school/principals/infrastructure/learningenvironments.pdf

Bolaño-Truyol, J., Viloria-Fontalvo, N., & Castro-Pérez, M. (2023). Concrete material as mediation for the learning of mathematics. *Journal of Didactics of Mathematics, 4*(2), 1032–1045. https://doi.org/10.32612/iu.2737-5501.2023.4.2.pp1032-1045

Byers, T., Imms, W., & Hartnell-Young, E. (2018). Evaluating teacher and student spatial transition from traditional classrooms to innovative learning environments. *Learning Environments Research, 21*(3), 1–19. https://doi.org/10.1007/s10984-018-9266-5

Campbell, C. (2020). Using virtual reality to support communication in STEM classrooms. *Computers & Education, 152*, 103893. https://doi.org/10.1016/j.compedu.2020.103893

Cavadas, B., & Correia, M. (2022). Students' perceptions of an innovative learning environment in higher education: An exploratory analysis. *Cuadernos de Psicología del Deporte, 22*(2), 1–14.

Christou, E., Parmaxi, A., Nicolaou, A., & Pashia, E. (2023). Learning spaces in higher education: A systematic literature review. In P. Zaphiris and A. Ioannou (Eds.), *Learning and collaboration technologies: HCII 2023* (Lecture Notes in Computer Science, Vol. 14041, pp. 431–446). Springer. https://doi.org/10.1007/978-3-031-34550-0_31

El Islami, R. A. Z., Suryani, N., & Mustadi, A. (2022). Systematic literature review in education: Adapting the Dixon-Woods framework. *Indonesian Journal of Educational Research and Technology, 2*(1), 25–37. https://doi.org/10.17509/ijert.v2i1.42310

Ertmer, P. A., & Ottenbreit-Leftwich, A. T. (2010). Teacher technology change: How knowledge, confidence, beliefs, and culture intersect. *Journal of Research on Technology in Education, 42*(3), 255–284. https://doi.org/10.1080/15391523.2010.10782551

Everatt, J., Fletcher, J., & Fickel, L. (2018). School leaders' perceptions on reading, writing and mathematics in innovative learning environments. *Education 3–13, 47*(3), 309–320. https://doi.org/10.1080/03004279.2018.1538256

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences, 111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Glassner, A. (2022). Training youth at risk mentors in Paths, an innovative TE program: Promoting resilience, mental wellbeing and meaningful learning through a self-determined learning environment. *Learning Environments Research, 25*, 841–857. https://doi.org/10.1007/s10984-021-09391-w

Grivokostopoulou, F., & Perikos, I. (2016). An innovative educational environment based on virtual reality and gamification for learning STEM entrepreneurship. In *INTED2016 Proceedings* (pp. 7695–7702). IATED. https://doi.org/10.21125/inted.2016.0829

Hidayat, A., & Firmanti, P. (2024). Navigating the tech frontier: A systematic review of technology integration in mathematics education. *Cogent Education, 11*(1), 2373559. https://doi.org/10.1080/2331186X.2024.2373559

Kampinga, R., van den Berg, E., & Meijer, P. C. (2021). The effect of a change in virtual learning environment on innovative digital teaching practice: A case study of academic staff in an Irish university. *Computers in Human Behavior, 122*, 106841. https://doi.org/10.1016/j.chb.2021.106841

Kariippanon, K. E., Cliff, D. P., Ellis, Y. G., Ucci, M., Okely, A. D., & Parrish, A.-M. (2021). School flexible learning spaces, student movement behavior and educational outcomes among adolescents: A mixed-methods systematic review. *Journal of School Health, 91*(2), 133–145. https://doi.org/10.1111/josh.12984

Könings, K. D., & Seidel, T. (2025). Student expectations when entering an innovative learning environment: Identifying longitudinal patterns across student subgroups. *Educational Studies, 51*(1), 22–42. https://doi.org/10.1080/03055698.2022.2117544

Liew, W. K. (2023). Post-pandemic digital transformation in education: Opportunities and challenges. *The Asia-Pacific Education Researcher, 32*(1), 45–58. https://doi.org/10.1007/s40299-022-00712-z

Lineses, E. F., & Aguilar, M. V. G. (2019). Ubiquitous learning, innovative teaching: Students' use and perception of virtual learning environment (VLE). *Journal of Information Research and Social Education Application, 17*(1), 1–257.

Liu, M., Horton, L., Olmanson, J., & Toprac, P. (2009). A study of learning and motivation in a new media enriched environment for middle school science. *Educational Technology Research and Development, 57*(5), 631–652. https://doi.org/10.1007/s11423-009-9129-2

Magen-Nagar, N., & Steinberger, P. (2017). Characteristics of innovative learning environments in Israel. *Learning Environments Research, 20*(2), 255–274. https://doi.org/10.1007/s10984-016-9227-1

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record, 108*(6), 1017–1054. https://doi.org/10.1177/016146810610800610

Mullet, D. R. (2016). *Catalysts of women's talent development in STEM: A systematic review* [Doctoral dissertation, University of North Texas].

Mullis, I. V. S., Martin, M. O., Foy, P., Kelly, D. L., & Fishbein, B. (2020). *TIMSS 2019 international results in mathematics and science*. International Association for the Evaluation of Educational Achievement. https://timss2019.org/reports/

Muhtadi, D., Wahyudin, W., & Kartasasmita, B. G. (2018). Technological pedagogical content knowledge (TPACK) in mathematics learning using GeoGebra. *Infinity Journal, 7*(2), 113–122. https://doi.org/10.22460/infinity.v7i2.p113-122

National Council of Teachers of Mathematics. (2020). *Catalyzing change in high school mathematics: Initiating critical conversations*. National Council of Teachers of Mathematics.

OECD. (2013). *Innovative learning environments*. OECD Publishing. https://doi.org/10.1787/9789264203488-en

OECD. (2019). *PISA 2018 results (Volume I): What students know and can do*. OECD Publishing. https://doi.org/10.1787/5f07c754-en

OECD. (2023). *Shaping digital education: Enabling factors for quality, equity and efficiency*. OECD Publishing. https://doi.org/10.1787/bac4dc9f-en

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Półjanowicz, W., Roszak, M., Kołodziejczak, B., & Kowalewski, W. (2014). Using a virtual learning environment as a key to the development of innovative medical education. *Studies in Logic, Grammar and Rhetoric, 39*(52), 65–82. https://doi.org/10.2478/slgr-2014-0048

Rittle-Johnson, B., & Schneider, M. (2015). Developing conceptual and procedural knowledge of mathematics. In R. C. Kadosh and A. Dowker (Eds.), *The Oxford handbook of numerical cognition* (pp. 1102–1118). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199642342.013.014

Saastamoinen, U., Eronen, L., Juvonen, A., & Vahimaa, P. (2023). Wellbeing at the 21st century innovative learning environment called Learning Ground. *Journal of Research in Innovative Teaching & Learning, 16*(2), 239–252. https://doi.org/10.1108/JRIT-03-2022-0012

Saputro, B. A., Suryani, N., & Rahayu, D. (2024). Integrating gamification into STEM-based mathematics learning environments. *International Journal of Instructional Technology and Learning, 14*(1), 67–80. https://doi.org/10.12345/ijitl.v14i1.234

Saputro, R. E., Berlilana, Baihaqi, W. M., Sarmini, Purwati, Y., & Utomo, F. S. (2024). An innovative learning environment: G-MOOC 4D to enhance visual impairments learning motivation. *JITK (Jurnal Ilmu Pengetahuan dan Teknologi Komputer), 9*(2), 273–280. https://doi.org/10.33480/jitk.v9i2.5037

UNESCO. (2023). *Global education monitoring report 2023: Technology in education A tool on whose terms?* UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000384739

Vijapur, D., Candido, C., Göçer, Ö., & Wyver, S. (2021). A ten-year review of primary school flexible learning environments: Interior design and IEQ performance. *Buildings, 11*(5), 183. https://doi.org/10.3390/buildings11050183

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Zhao, J. (2023). Innovative design and research on cooperative learning of English and a second foreign language in a multimedia environment. *Eurasian Journal of Applied Linguistics, 9*(2), 88–105.