

REVIEW ARTICLE

Artful Internet of Things in mathematics teacher education: A systematic review**Rusen Meylani*** 

Department of Educational Sciences, Ziya Gökalp Faculty of Education, Dicle University, Diyarbakir, Türkiye

(This article belongs to the *Special Issue: Mathematics Meets the Arts: Implications for teacher education*)**Abstract**

The rapid expansion of digital technologies has transformed educational landscapes, compelling educators to rethink how emerging tools can cultivate deeper learning, creativity, and innovation. Within this shift, the Internet of Things (IoT) has emerged as a transformative force, connecting physical and digital environments to enable interactive, data-driven, and learner-centered experiences. In mathematics education, IoT technologies invite new forms of exploration that blend computational thinking with artistic expression—an intersection increasingly recognized as vital for developing 21st-century teaching competencies and advancing the goals of sustainable and creative education. This systematic review explores how the IoT is being integrated into mathematics teacher education through the lens of artful thinking and creativity. Building on technological, sociocultural, and esthetic learning frameworks, the review critically synthesizes research published between 2015 and 2025. Findings revealed that IoT not only serves as a technological innovation but also as an artistic medium to foster imaginative, design-based mathematical practices among preservice and in-service teachers. Benefits identified include enhanced mathematical modeling, spatial reasoning, and interdisciplinary inquiry, while challenges include technological resistance, limited creative assessment models, and infrastructural inequalities. The review also emphasizes the potential of artfully connected IoT practices to advance Sustainable Development Goals 4 and 9. Recommendations are provided for future research, teacher education practices, and policy reforms aimed at embedding esthetic and technological creativity in mathematics instruction.

***Corresponding author:**Rusen Meylani
(rusen.meylani@dicle.edu.tr)**Citation:** Meylani R. Artful Internet of Things in mathematics teacher education: A systematic review. *Arts & Communication*. 2026;4(1):025190036. doi: 10.36922/AC025190036**Received:** May 6, 2025**Revised:** September 30, 2025**Accepted:** October 15, 2025**Published online:** October 29, 2025**Copyright:** © 2025 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons AttributionNoncommercial License, permitting all non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.**Publisher's Note:** AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.**Keywords:** Internet of Things; Mathematics teacher education; Artful thinking; Creative pedagogy; Smart classrooms; Sustainable education**1. Introduction****1.1. Background and rationale**

The Internet of Things (IoT) has increasingly permeated various sectors, profoundly reshaping practices and processes, including those in education, particularly within mathematics learning environments. By facilitating real-time data collection and enabling dynamic visualizations of abstract mathematical concepts, IoT extends

traditional educational boundaries and supports the adoption of innovative pedagogical approaches. Its integration into educational contexts not only improves technical efficiencies but also fosters interactive learning experiences that promote deeper engagement with mathematical content. However, it is important to recognize that many existing applications of IoT in education have predominantly emphasized operational efficiency, often at the expense of creativity, imagination, and interdisciplinary connections.¹⁻³

As mathematics education evolves to meet the complex demands of the 21st century, it becomes imperative to integrate artistic and creative dimensions into technological applications.^{2,4,5} The framework of artful thinking provides a critical pathway for enhancing this integration, encouraging both educators and learners to perceive mathematics not solely as a logical and procedural field but also as one rich with esthetic perspectives and design-based inquiry opportunities.^{4,6,7} This multidimensional approach necessitates creating educational environments where students are invited to navigate both technical and creative domains, thus cultivating well-rounded competencies essential for future educators.⁸⁻¹⁰

1.2. Gap analysis

Despite the considerable potential of IoT technologies in educational contexts, a substantial gap persists in the literature concerning their use to foster creative engagement within mathematics teacher education. Most studies have concentrated on the technical affordances of IoT, such as improving classroom management and enhancing analytical capabilities, while giving limited attention to its role in cultivating creative mathematical thinking and esthetic appreciation.¹¹⁻¹³ Furthermore, the intersection between IoT applications and creative pedagogical processes in mathematics education remains largely unexplored, with few systematic reviews addressing how these elements might be coherently integrated into teacher training programs.¹⁴⁻¹⁶

The lack of comprehensive investigations framing IoT within creative educational practices impedes the ability of educators to design programs that simultaneously develop technological proficiency and creative fluency among prospective mathematics teachers.¹⁶⁻¹⁸ Without such integration, instructional strategies risk remaining narrowly technical, rather than evolving into curricula that address the multifaceted challenges of modern education and adequately prepare students for complex learning environments.^{6,7,19} Addressing these deficiencies requires the development of pedagogical frameworks that elevate creativity alongside mathematical rigor, potentially transforming teacher education and enhancing student learning outcomes.^{5,20}

The urgency of pursuing mathematical creativity and innovative educational practices is reinforced by findings from multiple studies that advocate for pedagogical paradigms emphasizing creative problem-solving.^{1,12,21} These methodologies not only deepen cognitive engagement but also promote the kind of transformative pedagogical shifts increasingly necessary in mathematics education. Nevertheless, realizing this potential demands that educational institutions embrace curricula fostering creativity through interdisciplinary approaches and real-world problem-solving experiences.²²⁻²⁴ Therefore, a deliberate and concerted integration of creative pedagogical strategies within the technological frameworks provided through IoT is warranted to prepare a new generation of mathematics educators capable of delivering innovative, engaging, and contextually relevant learning experiences in an increasingly digitalized world.^{3,25-27}

1.3. Research questions

In light of the gaps identified, this systematic review seeks to address the following research questions:

- How is the IoT currently integrated into mathematics teacher education to foster both technical and creative competencies?
- In what ways does IoT support the development of artful thinking, imaginative reasoning, and esthetic engagement in mathematics teacher preparation programs?
- What pedagogical opportunities and challenges arise from the intersection of IoT, art, and mathematics education?

2. Data and methods

2.1. Data sources and search strategy

A comprehensive and systematic literature search was conducted to identify peer-reviewed studies focusing on the integration of IoT, artful thinking, and mathematics teacher education. The following databases were searched: Education Resources Information Center (ERIC), Scopus, Web of Science, IEEE Xplore, Education Source, and ArtsEdSearch. These databases were selected to ensure comprehensive coverage across education, technology, engineering, and arts-related research fields.

The search strategy employed Boolean operators, controlled vocabulary where applicable, and combinations of free-text terms. Key terms included: ("Internet of Things" OR "IoT") AND ("mathematics education" OR "math teacher education") AND ("art*" OR "creativ*" OR "design thinking" OR "esthetic*" OR "artful thinking"). Search strings were adapted to meet the specific indexing syntax of each database. Filters were applied to limit the

search to English-language studies published between January 01, 2015, and March 31, 2025.

In addition to database searching, a manual search of relevant conference proceedings, professional organization websites, and the reference lists of included studies was conducted to identify additional eligible studies that may not have been captured through the primary search. This supplementary search ensured that gray literature and emerging interdisciplinary research at the intersection of IoT, mathematics, and artful education were considered.

2.2. Inclusion and exclusion criteria

Strict inclusion and exclusion criteria were established to guide the selection process systematically. The inclusion criteria included:

- Peer-reviewed journal articles, conference papers, or significant organizational reports
- Studies involving preservice or in-service mathematics teachers
- Studies explicitly addressing the use of IoT technologies in mathematics education
- Studies incorporating elements of creativity, artistic expression, design thinking, or artful thinking in the context of IoT applications
- Studies reporting empirical research (quantitative, qualitative, or mixed methods) or comprehensive conceptual frameworks.

The exclusion criteria included:

- Studies focusing exclusively on technical or administrative applications of IoT without educational or artistic dimensions
- Studies not specifically related to mathematics education (e.g., general science, technology, engineering, and mathematics [STEM] education without a distinct focus on mathematics)
- Theoretical papers without empirical evidence, unless presenting a comprehensive, innovative framework linking IoT, art, and mathematics education
- Non-peer-reviewed sources, such as blog posts, non-academic magazines, editorials, and opinion pieces
- Publications not available in full-text or published in languages other than English without verified translations.

A two-stage screening process was implemented: first at the title and abstract level, and subsequently through full-text evaluation. Studies were included if they met all inclusion criteria after full-text assessment.

2.3. PRISMA selection process

A total of 986 records were initially identified through database searches, with an additional 18 records retrieved

through manual searches and reference lists, resulting in 1004 records overall. After the removal of duplicates, 820 records remained and were subjected to title and abstract screening. Of these, 698 records were excluded based on irrelevance to the research focus. Subsequently, 122 full-text articles were assessed for eligibility. During this stage, 45 articles were excluded for specific reasons: 19 articles did not integrate creativity or artful thinking, 13 were unrelated to mathematics teacher education, 8 demonstrated insufficient methodological quality, and 5 did not address IoT or relevant technologies. Ultimately, 77 studies met all inclusion criteria and were incorporated into the qualitative synthesis for the systematic review (Figure 1).

2.4. Data extraction and synthesis

Data extraction was guided by a structured protocol to ensure consistency and replicability. For each eligible study, the following information was systematically recorded:

- Author(s) and year of publication
- Country and educational context (preservice or in-service teacher education)
- Research aims and questions
- Study design and methodology (qualitative, quantitative, or mixed methods)
- Characteristics of participants (e.g., sample size and demographics)
- Description of IoT tools and technologies employed
- Description of artistic, creative, or design-based pedagogies integrated
- Main findings related to creativity, artful thinking, mathematical learning, and technological use
- Reported challenges, barriers, and limitations

The extracted data were then synthesized using a thematic analysis approach. Themes were identified inductively through iterative reading and coding of the extracted material. Attention was paid to patterns, convergences, divergences, and unique contributions across the included studies. Narrative synthesis was prioritized to maintain the richness of qualitative insights, while quantitative results were summarized descriptively when reported.

No meta-analysis was performed, as the heterogeneity of study designs, contexts, and outcome measures precluded meaningful statistical aggregation.

2.5. Quality appraisal

The methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT), which evaluates qualitative, quantitative, and mixed-methods research. The appraisal considered the appropriateness of research questions, suitability of study

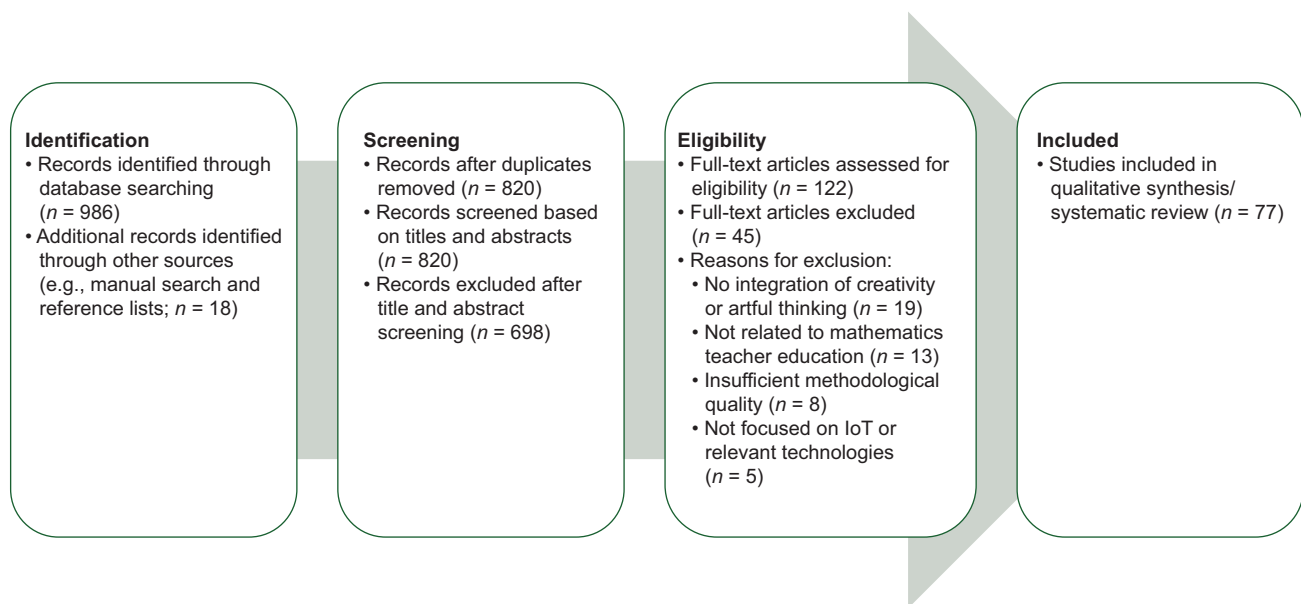


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram
Abbreviation: IoT: Internet of Things.

design, rigor of data collection and analysis, and clarity of reporting. Additional attention was given to the integration of creativity, esthetic dimensions, and interdisciplinary approaches, reflecting the thematic focus of this review.

To ensure reliability, the screening process was conducted in two stages, repeated at different time points, and coding decisions were cross-checked. Agreement rates reached a Cohen's kappa of 0.84, indicating strong consistency across rounds. Studies that failed to meet acceptable standards of methodological rigor, thematic alignment, or clarity were excluded at the full-text eligibility stage.

By combining MMAT criteria with supplementary considerations, such as reporting clarity and explicit connections to mathematics teacher education, this multi-criteria approach ensured that only studies with sufficient rigor and relevance were included in the final synthesis.

3. Results

Across the 77 unique references analyzed (Table 1 and Figure 2), the themes of pedagogical benefits of IoT integration and applications of IoT for creative mathematical practices emerged as the most substantial, comprising 24.04% and 22.40% of the total citations, respectively.

Although themes related to innovation and sustainability (15.30%) and artful conceptualizations (16.39%) were also notably represented, the significant presence of research on challenges and barriers (21.86%) reflects the field's ongoing struggle to balance innovation with practical

and ethical considerations. This distribution suggests that while creative integration of IoT into mathematics teacher education is a growing area of scholarly focus, there remains a strong parallel concern with infrastructure, ethics, and pedagogical readiness.

3.1. Artful conceptualizations of IoT in mathematics teacher education

This theme (Figure 3 and Table 2) accounted for 30 citations, representing 16.39% of the total references. Within this theme, IoT as a medium for creative and esthetic engagement was supported by 8 references (4.37%), while multisensory learning experiences through IoT and reframing mathematics as an interdisciplinary, artful endeavor were each represented by 11 references (6.01% each). These findings suggest that while interest in creativity and interdisciplinarity in IoT-enhanced mathematics education is growing, it still occupies a moderate proportion of the overall scholarly landscape.

3.1.1. IoT as a medium for creative and esthetic engagement

The IoT serves as a versatile medium that transcends technical functionalities, transforming mathematics education into a domain enriched with creativity and esthetic appreciation. Contemporary educational frameworks increasingly recognize IoT as a catalyst for imaginative exploration, enabling preservice teachers to engage with mathematics not solely as a logical construct but also as a field intertwined with artistic

Table 1. Classification of 77 reviewed studies by thematic focus and sub-thematic contributions

Main theme	Sub-theme	<i>n</i>	Percentage
Artful conceptualizations of IoT in mathematics teacher education	IoT as a medium for creative and esthetic engagement	8	4.37
	Multisensory learning experiences through IoT	11	6.01
	Reframing mathematics as an interdisciplinary, artful endeavor	11	6.01
	Subtotal	30	16.39
Applications of IoT to foster creative mathematical practices	Sensor-driven art installations illustrating mathematical concepts	8	4.37
	Wearable IoT technologies modeling dynamic mathematical relationships	9	4.92
	Arduino and Raspberry Pi projects connecting art, coding, and mathematics	10	5.46
	IoT-based real-world data collection for artistic interpretation	14	7.65
	Subtotal	41	22.40
Innovative and sustainable practices	Environmental data visualizations promoting ecological awareness	8	4.37
	Smart art installations addressing social and environmental themes	11	6.01
	Contributions to Sustainable Development Goals (SDG 4 and SDG 9)	9	4.92
	Subtotal	28	15.30
Pedagogical benefits of artfully integrated IoT	Strengthening mathematical modeling and visualization skills	10	5.46
	Development of design thinking and interdisciplinary problem-solving	11	6.01
	Enhancing engagement and affective connection to mathematics	11	6.01
	Fostering future-ready teaching competencies	12	6.56
	Subtotal	44	24.04
Challenges and barriers	Limited access to IoT infrastructure and technical expertise	8	4.37
	Resistance to open-ended and nontraditional pedagogies	11	6.01
	Difficulty assessing artistic and creative outcomes	10	5.46
	Ethical issues related to privacy, ownership, and data use	11	6.01
	Subtotal	40	21.86
Grand total		183	100.00

Abbreviation: IoT: Internet of Things.

Artful conceptualizations of IoT in mathematics teacher education	Applications of IoT to foster creative mathematical practices	Innovative and sustainable practices	Pedagogical benefits of artfully integrated IoT	Challenges and barriers
- IoT as a medium for creative and aesthetic engagement - Multisensory learning experiences through IoT - Reframing mathematics as an interdisciplinary, artful endeavor	- Sensor-driven art installations illustrating mathematical concepts - Wearable IoT technologies modeling dynamic mathematical relationships - Arduino and Raspberry Pi projects connecting art, coding, and mathematics - IoT-based real-world data collection for artistic interpretation	- Environmental data visualizations promoting ecological awareness - Smart art installations addressing social and environmental themes - Contributions to Sustainable Development Goals (SDG 4 and SDG 9)	- Strengthening mathematical modeling and visualization skills - Development of design thinking and interdisciplinary problem-solving - Enhancing engagement and affective connection to mathematics - Fostering future-ready teaching competencies	- Limited access to IoT infrastructure and technical expertise - Resistance to open-ended and nontraditional pedagogies - Difficulty assessing artistic and creative outcomes - Ethical issues related to privacy, ownership, and data use

Figure 2. Main themes and subthemes emerging from the thematic synthesis

Abbreviation: IoT: Internet of Things.

expression and human creativity.^{11,30,34} Research suggests that when educators incorporate IoT technologies, they foster environments conducive to the synthesis

of artistic and mathematical ideas, thereby bridging the gap between abstract mathematical concepts and tangible creative expressions.^{28,32} This integration not only

Table 2. The citations, along with their frequency and percentage, for the theme and its sub-themes

Main theme	Sub-theme	Citations	n	Percentage
Artful conceptualizations of IoT in mathematics teacher education	IoT as a medium for creative and esthetic engagement	Dhayanti <i>et al.</i> , ²⁸ Haavold <i>et al.</i> , ²⁹ Hamimi <i>et al.</i> , ³⁰ Ismiati, ³¹ Itqan and Arrahmani, ³² Khalid <i>et al.</i> , ¹¹ Simamora and Ramadhanta, ³³ Soomro <i>et al.</i> ³⁴	8	4.37
	Multisensory learning experiences through IoT	Bampasidis <i>et al.</i> , ³⁵ Chamberlin <i>et al.</i> , ³⁶ Hamid and Kamarudin, ³⁷ Hamimi <i>et al.</i> , ³⁰ Hoth <i>et al.</i> , ³⁸ Kuchkarova, ³⁹ Mamatnabiyev <i>et al.</i> , ⁴⁰ Mamazhanovich, ⁴¹ Mariani <i>et al.</i> , ⁴² Nilimaa, ⁴³ Suwastika <i>et al.</i> ⁴⁴	11	6.01
	Reframing mathematics as an interdisciplinary, artful endeavor	Berikzhanovna, ⁴⁵ Biçer, ⁴⁶ Bishara, ⁴⁷ Firmender <i>et al.</i> , ⁴⁸ Hamid and Kamarudin, ³⁷ Juliantara <i>et al.</i> , ⁴⁹ Kozłowski and Si, ⁵⁰ Lee and Heo, ⁵¹ Paneva-Marinova <i>et al.</i> , ⁵² Samritin <i>et al.</i> , ⁵³ Xayrullayevna ⁵⁴	11	6.01

Abbreviation: IoT: Internet of Things.

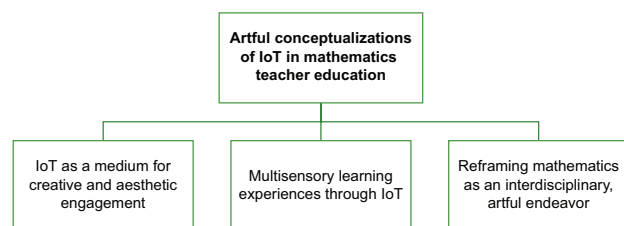


Figure 3. Visual depiction of the theme
Abbreviation: IoT: Internet of Things.

enriches mathematical understanding but also prepares preservice teachers to adopt interdisciplinary pedagogical approaches.²⁹

Positioning IoT as a medium for creative engagement aligns with modern educational aspirations to nurture esthetic sensitivity among preservice teachers. Through varied modalities—including visual arts, performance, and physical installations—students can experiment and express mathematical ideas creatively, thus reimagining mathematics within broader cultural and societal contexts.^{29,31,33} Strategic integration of IoT technology invites educators to expand pedagogical boundaries, promoting innovative teaching approaches that resonate with the creativity inherent in both art and mathematics.³³

3.1.2. Multisensory learning experiences through IoT

Studies have consistently demonstrated the capacity of IoT technologies to facilitate multisensory learning experiences by combining visual, auditory, and tactile stimuli to enhance comprehension of mathematical constructs.^{30,36,40} By employing IoT devices, educators can deliver interactive lessons that engage preservice teachers through diverse sensory modalities. For instance, environmental sensors can record real-time data such as sound levels, temperature changes, and motion, providing dynamic contexts for mathematical exploration.^{37,42}

Multisensory engagement deepens cognitive connections among learners, supporting a richer internalization of

complex mathematical ideas.^{35,38,41} Activating multiple senses stimulates curiosity and innovation while fostering holistic comprehension of mathematical theories. Integrating sensory-rich pedagogical strategies, therefore, supports the development of both foundational mathematical competencies and creative exploration within teacher education programs.^{39,43,44}

3.1.3. Reframing mathematics as an interdisciplinary, artful endeavor

The integration of IoT technologies reframes mathematics as an interdisciplinary field, emphasizing its connections to art, design, culture, and human expression.^{50,52,54} Through IoT tools, preservice teachers can explore how mathematical modeling underpins artistic creations such as digital art, installations, and kinetic sculptures.^{37,53} This interdisciplinary engagement fosters intellectual flexibility and enriches preservice teachers' understanding of mathematics as a dynamic, culturally embedded practice.⁴⁷

Incorporating broader societal and artistic contexts into mathematical education helps dismantle perceptions of mathematics as isolated and rigid.^{49,51} Consequently, preservice teachers are better equipped to design innovative, technology-enhanced learning experiences that emphasize adaptability and multidimensional inquiry.^{45,46,48}

3.2. Applications of IoT to foster creative mathematical practices

A total of 41 references (22.40%) contributed to this theme (Figure 4 and Table 3). Among the sub-themes, IoT-based real-world data collection for artistic interpretation was the most prominent, with 14 citations (7.65%), highlighting the growing emphasis on real-world, data-driven creative learning. Arduino and Raspberry Pi projects were discussed in 10 studies (5.46%), followed by Wearable IoT technologies with 9 citations (4.92%) and Sensor-driven art installations with 8 citations (4.37%). The relatively high representation of this theme reflects a strong scholarly

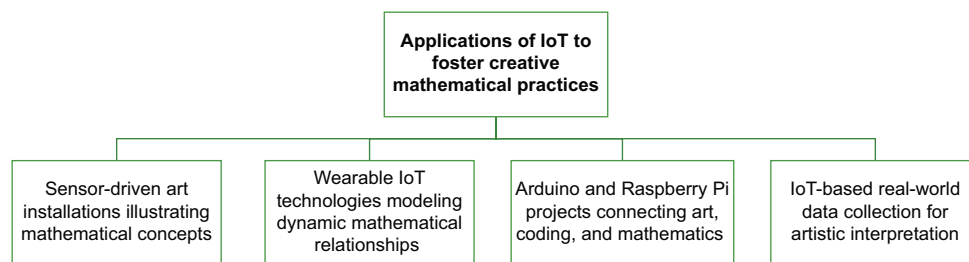


Figure 4. Visual depiction of the theme
Abbreviation: IoT: Internet of Things.

Table 3. The citations, along with their frequency and percentage, for the theme and its sub-themes

Main theme	Sub-theme	Citations	n	Percentage
Applications of IoT to foster creative mathematical practices	Sensor-driven art installations illustrating mathematical concepts	Berikzhanovna; ⁴⁵ Akar; ⁵⁵ Itqan and Arrahmani; ³² Kozlowski and Si; ⁵⁰ Poudel; ⁵⁶ Samritin <i>et al.</i> ; ⁵³ Simamora and Ramadhanta; ³³ Wahyuni <i>et al.</i> ⁵⁷	8	4.37
	Wearable IoT technologies modeling dynamic mathematical relationships	Applebaum; ^{58,59} Arnellis <i>et al.</i> ; ⁶⁰ Bampasidis <i>et al.</i> ; ³⁵ Bardhan; ⁶¹ Itqan and Arrahmani; ³² Laili and Istikomah; ⁶² Suwastika <i>et al.</i> ; ⁴⁴ Vasconcelos; ⁶³ Yaftian ⁶⁴	9	4.92
	Arduino and Raspberry Pi projects connecting art, coding, and mathematics	Bruhn and Lüken; ⁶⁵ Connolly <i>et al.</i> ; ⁶⁶ Hoth <i>et al.</i> ; ³⁸ Jalil and Siew; ⁶⁷ Kuchkarova; ³⁹ Metu <i>et al.</i> ; ⁶⁸ Qian and Cheng; ⁶⁹ Simamora and Ramadhanta; ³³ Supandi <i>et al.</i> ; ⁷⁰ Šimon and Gogolák ⁷¹	10	5.46
	IoT-based real-world data collection for artistic interpretation	Bampasidis <i>et al.</i> ; ³⁵ Bezerra <i>et al.</i> ; ⁷² Dhayanti <i>et al.</i> ; ²⁸ Huê <i>et al.</i> ; ⁷³ Jorge <i>et al.</i> ; ⁷⁴ Juliantara <i>et al.</i> ; ⁴⁹ Kelechi and Nnaji; ⁷⁵ Kuchkarova; ³⁹ Laili and Istikomah; ⁶² Makuseva <i>et al.</i> ; ⁴² Mariani <i>et al.</i> ; ⁴² Monahan <i>et al.</i> ; ⁷⁷ Qizi; ⁷⁸ Unterfrauner <i>et al.</i> ⁷⁹	14	7.65

Abbreviation: IoT: Internet of Things.

interest in practical and artistic applications of IoT in mathematics education.

3.2.1. Sensor-driven art installations illustrating mathematical concepts

Sensor-driven art installations utilizing IoT technologies represent an innovative method for visualizing core mathematical principles. Through such initiatives, preservice teachers can physically manipulate and engage with concepts such as geometric transformations, data patterns, and spatial reasoning, linking abstract mathematics to tangible artistic outputs.^{32,53} These installations offer dynamic platforms where mathematical ideas become living, interactive experiences, fostering deeper understanding while simultaneously stimulating creative expression.^{45,55}

Engaging in these projects encourages preservice teachers to collaborate, think critically, and design esthetically compelling yet mathematically sound artifacts.^{50,56} The interdisciplinary nature of sensor-driven projects underscores the importance of fostering connections between mathematics, creativity, and technology.^{33,57} By incorporating such experiences into mathematics teacher education, programs can cultivate richer learning environments that build both technical and artistic competencies.

3.2.2. Wearable IoT technologies modeling dynamic mathematical relationships

Wearable IoT technologies provide another powerful avenue for modeling dynamic mathematical phenomena, such as rates of change, symmetry, and motion. These applications allow preservice teachers to experience mathematics firsthand, gathering and interpreting real-time data to uncover underlying principles and relationships.^{32,61,63} Engaging with wearable devices transforms learning into an active exploration, moving beyond passive theoretical instruction toward experiential discovery.^{35,64}

This hands-on approach promotes the development of critical thinking, data literacy, and problem-solving skills, empowering future educators to create dynamic classroom environments that encourage active participation.^{44,58,59,62} Integrating wearable IoT technologies thus nurtures teaching practices that align with contemporary educational demands for innovation, engagement, and applied learning.⁶⁰

3.2.3. Arduino and Raspberry Pi projects connecting art, coding, and mathematics

Low-cost IoT platforms, such as Arduino and Raspberry Pi, facilitate hands-on projects that bridge art, coding,

and mathematics. Through these technologies, preservice teachers construct artistic representations of mathematical concepts, developing computational thinking alongside creative expression.^{33,70} Such projects encourage participants to integrate programming skills with mathematical reasoning, resulting in multifaceted, interdisciplinary learning experiences.^{38,68}

Moreover, these initiatives promote collaboration, experimentation, and iterative problem-solving, vital components of innovative educational practices.^{66,69} By blending artistic creation with technological skills, preservice teachers cultivate a growth mindset and foster a willingness to explore the exploratory nature of mathematics.^{39,67,71} The creative use of Arduino and Raspberry Pi thus transforms mathematics education into an engaging, multidimensional endeavor.⁶⁵

3.2.4. IoT-based real-world data collection for artistic interpretation

Projects utilizing IoT devices for real-world data collection enable preservice teachers to engage in authentic mathematical inquiries anchored in empirical realities. Through environmental sensors and data-gathering tools, students collect information that can be analyzed, interpreted, and visualized artistically.^{35,73,77} This process fosters interdisciplinary learning by linking mathematics, science, and art through creative interpretations of data.^{72,74,79}

Engagement with empirical data promotes the perception of mathematics as an integral part of daily life, enhancing students' problem-solving strategies and esthetic sensibilities.^{42,62} Real-world data-driven artistic projects motivate learners by allowing them to creatively address societal issues through mathematical inquiry.^{39,49,75} Integrating IoT into mathematics education thus fosters innovation, real-world relevance, and interdisciplinary competencies.^{28,76,78}

3.3. Innovative and sustainable practices

This theme (Figure 5 and Table 4) included 28 citations (15.30%). Smart art installations addressing social and

environmental themes led with 11 references (6.01%), demonstrating a significant intersection between mathematical creativity and broader social issues. Environmental data visualizations promoting ecological awareness and Contributions to Sustainable Development Goals (SDG 4 and SDG 9) were represented by 8 (4.37%) and 9 (4.92%) references, respectively. These results emphasize the increasing integration of sustainability and global citizenship within mathematics education discourse.

3.3.1. Environmental data visualizations promoting ecological awareness

Projects that utilize IoT technologies to collect and visualize environmental data offer significant opportunities to link sustainability education with mathematics learning. By engaging preservice teachers in collecting real-world data on factors such as air quality, temperature changes, and resource consumption, educational programs deepen learners' understanding of mathematical applications while simultaneously fostering ecological awareness.^{32,69} These visualizations not only provide esthetic representations of environmental phenomena but also serve as powerful educational tools that underscore the societal relevance of mathematics.^{39,61}

Integrating ecological data collection into mathematics education encourages preservice teachers to view sustainability not as a peripheral topic but as an essential, embedded component of their instructional practices.^{11,57} Project-based learning modules that involve artistic

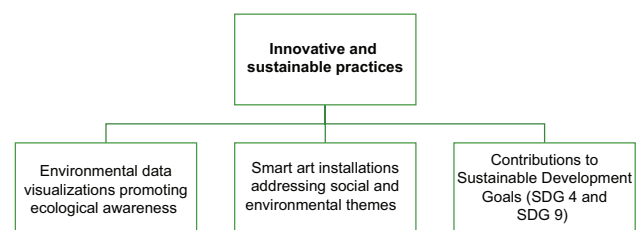


Figure 5. Visual depiction of the theme
Abbreviation: IoT: Internet of Things.

Table 4. The citations, along with their frequency and percentage, for the theme and its sub-themes

Main theme	Sub-theme	Citations	n	Percentage
Innovative and sustainable practices	Environmental data visualizations promoting ecological awareness	Bardhan; ⁶¹ Hamid and Kamarudin; ³⁷ Itqan and Arrahmani; ³² Khalid <i>et al.</i> ; ¹¹ Kuchkarova; ³⁹ Paneva-Marinoval <i>et al.</i> ; ⁵² Qian and Cheng; ⁶⁹ Wahyuni <i>et al.</i> ⁵⁷	8	4.37
	Smart art installations addressing social and environmental themes	Chamberlin <i>et al.</i> ; ³⁶ Chacón <i>et al.</i> ; ⁸⁰ Haavold <i>et al.</i> ; ²⁹ Jalil and Siew; ⁶⁷ Juliantara <i>et al.</i> ; ⁴⁹ Kuchkarova; ³⁹ Poudel; ⁵⁶ Simamora and Ramadhanta; ³³ Šimon and Gogolák; ⁷¹ Suyitno; ⁸¹ Wadaani ⁵	11	6.01
	Contributions to Sustainable Development Goals (SDG 4 and SDG 9)	Anita; ⁸² Arnellis <i>et al.</i> ; ⁶⁰ Hamid and Kamarudin; ³⁷ Hamimi <i>et al.</i> ; ³⁰ Ismiati; ³¹ Itqan and Arrahmani; ³² Khalid <i>et al.</i> ; ¹¹ Kozłowski and Si; ⁵⁰ Suwastika <i>et al.</i> ⁴⁴	9	4.92

Abbreviation: IoT: Internet of Things.

interpretations of environmental data can further inspire a sense of ethical stewardship and community engagement among future educators.^{37,52} By situating mathematics within the broader context of environmental responsibility, teacher education programs contribute to the development of educators who are committed to fostering sustainable practices.

3.3.2. Smart art installations addressing social and environmental themes

Preservice teachers increasingly utilize IoT technologies to create smart art installations that address pressing social and environmental issues, demonstrating the potential of mathematics education to serve as a catalyst for societal change.^{5,33,56} These projects integrate mathematical inquiry with critical ethical, social, and environmental considerations, illustrating the discipline's capacity to engage with broader human concerns.^{29,67}

By developing installations that provoke dialogue among peers and community members, preservice teachers model ways in which mathematics and creativity can inspire civic engagement and activism.^{39,49,81} These experiences cultivate a sense of agency among future educators, empowering them to design learning experiences that are not only academically rigorous but also socially relevant and transformative.^{36,71,80}

3.3.3. Contributions to SDG 4 and SDG 9

The creative integration of IoT technologies within mathematics teacher education aligns directly with key SDGs, particularly SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure).^{11,32,37} By embedding technological and artistic creativity into instructional methodologies, teacher education programs cultivate future educators who are equipped to drive innovation and promote educational equity on a global scale.

Research emphasizes that the integration of arts and technology within mathematics fosters higher levels of engagement, critical thinking, and interdisciplinary competence, all of which are necessary to achieve sustainable educational outcomes.^{30,44,60} By embracing these opportunities, preservice teachers can contribute meaningfully to the advancement of inclusive, high-quality education while fostering the innovation needed to address future societal challenges.^{31,50,82}

Consequently, mathematics teacher education that incorporates IoT and creative practices not only prepares educators for contemporary classrooms but also empowers them to actively participate in the global movement toward achieving the SDGs.

3.4. Pedagogical benefits of artfully integrated IoT

This theme, which focused on pedagogical impacts (Figure 6 and Table 5), comprised the largest share of the literature (44 citations; 24.04%). Fostering future-ready teaching competencies was the most frequently cited sub-theme with 12 references (6.56%). Both development of design thinking and interdisciplinary problem-solving and enhancing engagement and affective connection to mathematics had 11 citations each (6.01%), while strengthening mathematical modeling and visualization skills was represented by 10 citations (5.46%). This dominant presence underscores the field's recognition of IoT and creative practices as transformative tools for enhancing teacher competencies.

3.4.1. Strengthening mathematical modeling and visualization skills

Engaging preservice teachers with artfully integrated IoT projects significantly enhances their abilities to model, visualize, and represent mathematical ideas in innovative and tangible ways.^{48,78,84} These experiences encourage future educators to explore mathematics through multiple artistic and technological lenses, thus strengthening critical instructional competencies. Through hands-on exploration, preservice teachers acquire practical strategies for translating complex mathematical concepts into accessible and engaging formats for diverse learners.⁸³

The emphasis on visualization nurtures a deeper conceptual understanding, equipping preservice teachers with skills necessary for effective mathematical communication in classroom settings.^{11,61,63} This proficiency in visualization not only supports preservice teachers' professional growth but also prepares them to foster similar abilities among their students, promoting a cycle of creative, inquiry-driven mathematical learning.^{43,57,65}

3.4.2. Development of design thinking and interdisciplinary problem-solving

The creative demands associated with artfully integrating IoT technologies cultivate essential skills in design thinking, interdisciplinary collaboration, and solution-focused inquiry.^{45,46,64} By engaging with innovative projects, preservice teachers are required to generate, test, and refine ideas while integrating diverse disciplinary perspectives, mirroring real-world problem-solving scenarios. This design-oriented mindset fosters adaptive thinking and creativity, vital attributes for contemporary educators.^{63,81,87}

Exposure to interdisciplinary approaches expands preservice teachers' pedagogical toolkits, enabling them to construct rich, multifaceted learning experiences that transcend traditional subject boundaries.^{44,86} As future educators encounter complex, open-ended challenges,

Table 5. The citations, along with their frequency and percentage, for the theme and its sub-themes

Main theme	Sub-theme	Citations	n	Percentage
Pedagogical benefits of artfully integrated IoT	Strengthening mathematical modeling and visualization skills	Bardhan; ⁶¹ Bruhn and Lüken; ⁶⁵ Firmender <i>et al.</i> ; ⁴⁸ Khalid <i>et al.</i> ; ¹¹ Munaji <i>et al.</i> ; ⁸³ Nadiroh; ⁸⁴ Nilimaa; ⁴³ Qizi; ⁷⁸ Vasconcelos; ⁶³ Wahyuni <i>et al.</i> ⁵⁷	10	5.46
	Development of design thinking and interdisciplinary problem-solving	Berikzhanovna; ⁴⁵ Annet; ⁸⁵ Bampasidis <i>et al.</i> ; ³⁵ Biçer; ⁴⁶ Pasaribu <i>et al.</i> ; ⁸⁶ Sekinaeva; ⁸⁷ Suwastika <i>et al.</i> ; ⁴⁴ Suyitno; ⁸¹ Vasconcelos; ⁶³ Yaftian; ⁶⁴ Zuhri ⁸⁸	11	6.01
	Enhancing engagement and affective connection to mathematics	Berikzhanovna; ⁴⁵ Arnellis <i>et al.</i> ; ⁶⁰ Haavold <i>et al.</i> ; ²⁹ Hamid and Kamarudin; ³⁷ Metu <i>et al.</i> ; ⁶⁸ Milner-Bolotin and Zazkis; ⁸⁹ Pasaribu <i>et al.</i> ; ⁸⁶ Samaniego <i>et al.</i> ; ⁹⁰ Seftiana <i>et al.</i> ; ⁹¹ Sekinaeva; ⁸⁷ Yang ⁹²	11	6.01
	Fostering future-ready teaching competencies	Applebaum; ^{58,59} Bampasidis <i>et al.</i> ; ³⁵ Haavold <i>et al.</i> ; ²⁹ Hoth <i>et al.</i> ; ³⁸ Kozłowski and Si; ⁵⁰ Kuchkarova; ³⁹ Laili and Istikomah; ⁶² Mariani <i>et al.</i> ; ⁴² Qian and Cheng; ⁶⁹ Saraç and Özdener; ⁹³ Sekinaeva; ⁸⁷ Stylianidou <i>et al.</i> ⁹⁴	12	6.56

Abbreviation: IoT: Internet of Things.

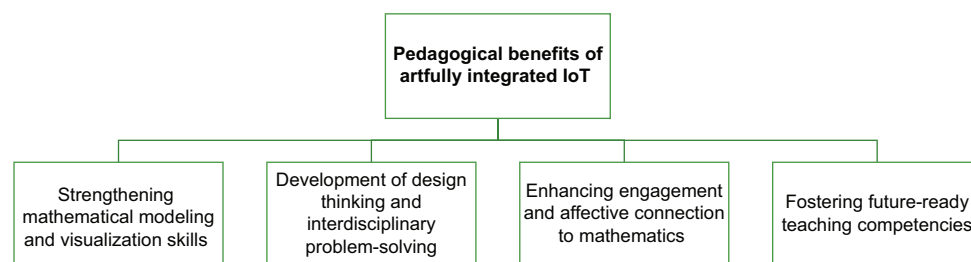


Figure 6. Visual depiction of the theme

Abbreviation: IoT: Internet of Things.

they develop resilience and flexibility, attributes that are increasingly demanded in today's evolving educational environments.^{35,85,88}

3.4.3. Enhancing engagement and affective connection to mathematics

Participation in IoT-based artistic projects has been shown to enhance preservice teachers' engagement, enjoyment, and emotional connection to mathematics.^{37,68,89} These affective benefits are critical, as they reframe mathematics from a static body of knowledge into a dynamic, expressive, and personally meaningful discipline. By fostering environments that emphasize creativity, educators can demystify mathematics and increase its accessibility to a broader range of learners.^{86,87,90}

Strengthening students' emotional connection to mathematics also promotes persistence, resilience, and creative risk-taking—qualities that are essential for success in complex problem-solving contexts.^{29,92} Furthermore, engaging in artistic exploration builds self-efficacy among preservice teachers, encouraging them to adopt creativity as a core component of their pedagogical identity.^{45,60,91}

3.4.4. Fostering future-ready teaching competencies

Creative IoT activities play a pivotal role in preparing preservice teachers for future instructional environments that

prioritize innovation, multimodal learning, and technological fluency.^{50,87,94} Engagement with IoT-driven projects cultivates adaptability, equipping future educators to meet the growing demands for creative and flexible teaching practices.^{29,39,42}

Developing a nuanced understanding of how technology can support creative teaching and learning processes positions preservice teachers to enrich their students' educational experiences meaningfully.^{35,62,69} As mathematics education evolves to embrace digital tools and interdisciplinary approaches, preservice teachers trained through IoT integration will be better prepared to contribute to sustainable, student-centered educational reforms.^{38,58,59,93}

3.5. Challenges and barriers

Finally, 40 citations (21.86%) addressed challenges and barriers (Figure 7 and Table 6). Resistance to open-ended and nontraditional pedagogies and ethical issues related to privacy, ownership, and data use each appeared in 11 studies (6.01%), illustrating ongoing tensions surrounding educational innovation. Difficulty assessing artistic and creative outcomes was discussed in 10 studies (5.46%), and limited access to IoT infrastructure and technical expertise was highlighted in 8 references (4.37%). The substantial attention to challenges signals a critical need for systematic support and policy development to facilitate the adoption of creative IoT-based pedagogies.

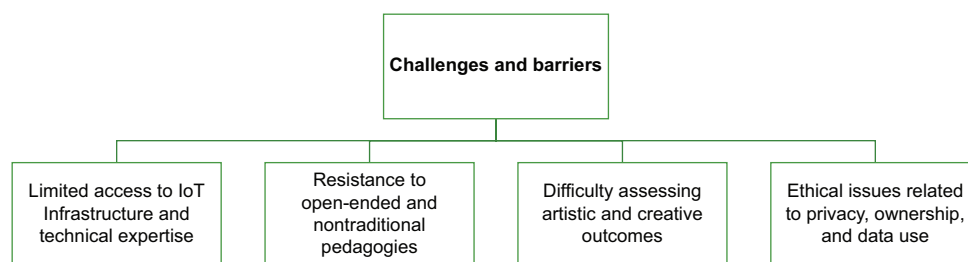


Figure 7. Visual depiction of the theme
Abbreviation: IoT: Internet of Things.

Table 6. The citations, along with their frequency and percentage, for the theme and its sub-themes

Main theme	Sub-theme	Citations	n	Percentage
Challenges and barriers	Limited access to IoT infrastructure and technical expertise	Biçer; ⁴⁶ Hamimi <i>et al.</i> ; ³⁰ Mamazhanovich; ⁴¹ Monahan <i>et al.</i> ; ⁷⁷ Pasaribu <i>et al.</i> ; ⁸⁶ Saraç and Özdenler; ⁹³ Utami <i>et al.</i> ; ⁹⁵ Wahyuni <i>et al.</i> ⁵⁷	8	4.37
	Resistance to open-ended and nontraditional pedagogies	Akar; ⁵⁵ Applebaum; ^{58,59} Biçer; ⁴⁶ Chamberlin <i>et al.</i> ; ³⁶ Chacón <i>et al.</i> ; ⁸⁰ Lee and Heo; ⁵¹ Mamazhanovich; ⁴¹ Pasaribu <i>et al.</i> ; ⁸⁶ Saraç and Özdenler; ⁹³ Sekinaeva; ⁸⁷ Supandi <i>et al.</i> ⁷⁰	11	6.01
	Difficulty assessing artistic and creative outcomes	Akar; ⁵⁵ Gorev <i>et al.</i> ; ⁹⁶ Juliantara <i>et al.</i> ; ⁴⁹ Maro <i>et al.</i> ; ⁹⁷ Monahan <i>et al.</i> ; ⁷⁷ Poudel; ⁵⁶ Setiyawan <i>et al.</i> ; ⁹⁸ Utami <i>et al.</i> ; ⁹⁵ Winarko; ⁹⁹ Yafian ⁶⁴	10	5.46
	Ethical issues related to privacy, ownership, and data use	Biçer; ⁴⁶ Daskolia <i>et al.</i> ; ¹⁰⁰ Mamazhanovich; ⁴¹ Maro <i>et al.</i> ; ⁹⁷ Monahan <i>et al.</i> ; ⁷⁷ Sakabe <i>et al.</i> ; ¹⁰¹ Suwastika <i>et al.</i> ; ⁴⁴ Syutaridho <i>et al.</i> ; ¹⁰² Vasconcelos; ⁶³ Yafian; ⁶⁴ Šimon and Gogolák ⁷¹	11	6.01

Abbreviation: IoT: Internet of Things.

3.5.1. Limited access to IoT infrastructure and technical expertise

One of the foremost challenges in integrating IoT technologies into mathematics teacher education is the unequal access to necessary infrastructure and technical expertise.^{41,57,86} Variations in the availability of IoT devices, technical support, and professional development opportunities across educational institutions impact the consistency and quality of implementation. Limited resources hinder preservice teachers' exposure to creative and innovative uses of IoT technologies.^{77,95}

In addition, insufficient technical know-how among educators often poses a barrier to the successful adoption of IoT initiatives. Concerns about rapidly evolving technological requirements and the need for continuous professional development further exacerbate this challenge. To address these limitations, teacher education programs must prioritize investment in IoT infrastructure and provide ongoing training to ensure that preservice teachers can confidently and competently integrate IoT into their instructional practices.^{30,46,93}

3.5.2. Resistance to open-ended and nontraditional pedagogies

Despite the growing emphasis on creativity and innovation, resistance to open-ended and nontraditional pedagogical

approaches persists among both faculty members and students.^{36,41,51} Deep-rooted preferences for traditional, procedural methods of mathematics instruction often result in skepticism or reluctance toward exploratory, IoT-enhanced, and art-integrated pedagogies. This resistance can hinder the adoption of more creative instructional practices and stifle innovation within teacher preparation programs.^{46,58,59,86}

Promoting cultural change within educational institutions is essential for fostering acceptance of progressive teaching approaches that combine rigor with creativity. Integrating discussions of pedagogical diversity, interdisciplinary collaboration, and the value of creativity into preservice curricula can help mitigate resistance and prepare future educators to embrace holistic and adaptive teaching strategies.^{55,70,80,87,93}

3.5.3. Difficulty assessing artistic and creative outcomes

Conventional assessment frameworks used in mathematics education often prove inadequate for evaluating artistic and creative outcomes emerging from IoT-based projects.^{55,77,95,99} Traditional grading systems, focused predominantly on accuracy and procedural proficiency, are ill-suited to capture the multifaceted and process-oriented nature of creative learning experiences. As a result, educators may

struggle to fairly and effectively assess student growth and achievement in projects that emphasize innovation, artistic expression, and interdisciplinary inquiry.^{56,64}

To address this challenge, educational programs must develop and implement innovative assessment models that value creativity, collaboration, and problem-solving as integral components of mathematical learning.^{49,97,98} Holistic assessment frameworks that recognize the complexity and depth of creative mathematical work will better support the aims of integrated IoT education and encourage sustained engagement with artistic mathematical practices.⁹⁶

3.5.4. Ethical issues related to privacy, ownership, and data use

The implementation of IoT technologies in educational contexts also raises critical ethical concerns related to data privacy, intellectual property rights, and the responsible use of student-generated content.^{77,97,102} IoT devices often collect and transmit sensitive information, making it imperative to establish clear policies that protect the rights and privacy of all participants involved in creative educational projects.^{63,100,101}

Institutions must proactively develop guidelines that address ownership of artistic creations, consent for data use, and ethical considerations surrounding the collection and dissemination of information.^{41,44} Moreover, teacher education programs should embed discussions on ethics into their curricula to equip preservice teachers with the critical awareness needed to navigate these challenges responsibly.^{46,64,71} Cultivating ethical literacy will empower future educators to integrate IoT technologies thoughtfully and respectfully, upholding the dignity and rights of all learners.

4. Discussion

4.1. Synthesis of findings across studies

4.1.1. IoT as a bridge between technology, art, and mathematics education

The synthesis of findings across multiple studies indicates that the IoT serves as a compelling bridge connecting technological innovation, artistic creativity, and mathematical reasoning. Rather than functioning merely as a technical enhancement, IoT enables the creation of learning experiences where mathematics is expressed, interpreted, and understood through various artistic media.¹⁰³ This integration allows students to visualize and manipulate abstract mathematical concepts, fostering environments where technology and art intertwine seamlessly with mathematics education.¹⁰⁴

Collectively, the findings highlight the transformative potential of such integrative approaches, suggesting that when mathematics is infused with creative and artistic elements, it significantly enhances student engagement and deepens understanding.¹⁰⁵ Furthermore, IoT technologies facilitate dynamic, multisensory interactions between students and mathematical ideas, fostering stronger cognitive and emotional connections to the discipline.¹⁰⁶ This transition reflects a broader pedagogical shift, emphasizing the importance of integrating technology with artistic practices to create richer and more inclusive learning environments.¹⁰⁷

4.1.2. Artful thinking as a catalyst for reimagining mathematics teacher preparation

The incorporation of artful thinking frameworks challenges traditional models of mathematics teacher preparation by emphasizing the creative, imaginative, and interdisciplinary dimensions of education.¹⁰⁸ Research demonstrates that preservice teachers trained within artful thinking frameworks are better equipped to design student-centered environments that foster critical thinking, exploration, and creativity.¹⁰⁹

This paradigm shift encourages viewing mathematics as a narrative shaped by inquiry and artistic interpretation rather than rigid procedural mastery.¹¹⁰ Integrating artful thinking also fosters an appreciation of the interconnectedness of disciplines, positioning mathematics within broader cultural and societal contexts.¹¹¹ Consequently, this approach enriches the learning process by embedding creativity and esthetic engagement as essential components of mathematics education.¹¹²

4.1.3. Expanding affective and esthetic dimensions of mathematics learning

Artful IoT practices contribute to a more holistic vision of mathematics education by valuing emotional, imaginative, and experiential dimensions alongside cognitive skills.¹¹³ Research indicates that preservice teachers exposed to multisensory, esthetic experiences exhibit higher engagement and motivation levels.¹¹⁴ These experiences help learners develop deeper emotional connections to mathematics, enabling them to appreciate the discipline's broader cultural and societal significance.¹¹⁵

Moreover, multisensory engagement fosters a classroom climate where exploration and creativity are integral to the learning process.¹¹⁶ Through these approaches, mathematics education can move beyond computations and algorithms, revealing the inherent beauty and artistry within the discipline.¹¹⁷

4.2. Theoretical implications

Theoretical perspectives on IoT integration in mathematics teacher education highlight the need to expand traditional pedagogical frameworks to embrace creativity, sociocultural mediation, and sustainability. Extending established models such as Technological Pedagogical Content Knowledge (TPACK), grounding practices in sociocultural theory, and embedding innovation and responsible citizenship within mathematics education offer new pathways for transformative teaching. Together, these approaches position preservice teachers to navigate complex educational landscapes while fostering critical, creative, and socially responsive learning environments.

4.2.1. Extending TPACK through creative and esthetic competencies

Findings suggest that established models, such as the TPACK framework, should be expanded to incorporate creative and esthetic competencies as fundamental dimensions.¹¹⁸ Research shows that the intersection of creativity, technology, and pedagogy is vital for cultivating effective teaching practices in contemporary classrooms.¹¹⁹ Future models must recognize how IoT and artful thinking reshape pedagogical strategies, enabling educators to integrate creative inquiry effectively.¹²⁰ This broader conceptualization will enhance mathematics teacher education and benefit cross-disciplinary educational innovation.

4.2.2. Sociocultural mediation of technological and artistic experiences

Grounded in sociocultural theory, the use of IoT as an artistic and communicative mediator broadens the role of cultural tools in learning.¹²¹ Integrating artful IoT practices demonstrates how digital technologies mediate meaning-making processes across disciplines, facilitating deeper cultural and contextual understandings.¹²² Teacher education must therefore prepare preservice teachers to navigate diverse learning landscapes where sociocultural and technological mediations intersect meaningfully.

4.2.3. Mathematics education within a sustainability and innovation paradigm

Embedding sustainability-oriented artful projects using IoT technologies calls for a reconceptualization of mathematics education within global frameworks emphasizing innovation and responsible citizenship.¹²³ Mathematics education has a vital role in fostering the critical thinking and interdisciplinary collaboration needed to address global challenges.¹²⁴ Preparing preservice teachers to integrate sustainability themes into mathematics education is essential for cultivating engaged citizens capable of shaping a more equitable future.¹²⁵

4.3. Practical implications for mathematics teacher education

The integration of artful IoT projects into preservice mathematics teacher education represents a critical step toward fostering creativity, innovation, and technological fluency among future educators. To fully realize this potential, institutions must not only embed such projects into their curricula but also provide the necessary infrastructure, sustained professional development, and interdisciplinary collaboration opportunities. Together, these strategies create a foundation for preparing teachers who can navigate and shape dynamic, interconnected, and future-ready learning environments. Details of strategies are as follows:

- Embedding artful IoT projects into preservice curricula: Mathematics teacher education programs should deliberately embed artful IoT projects into their curricula, promoting design thinking, creative inquiry, and technological literacy.¹²⁶ Such initiatives offer preservice teachers opportunities to engage with real-world problems, thereby enhancing professional preparation.¹²⁷
- Providing infrastructure and professional development for artful IoT integration: Institutions must invest in IoT infrastructure and offer comprehensive professional development programs that address both technical skills and creative pedagogies.¹²⁸⁻¹³⁰ Sustained support structures are essential for fostering the confidence and competence necessary for innovative teaching practices.¹³¹
- Encouraging interdisciplinary collaboration and innovation: Mathematics education should embrace interdisciplinary models by facilitating collaboration across education, engineering, fine arts, and sustainability disciplines.¹³² Such collaborations enhance preservice teachers' abilities to design dynamic, interconnected learning environments.¹³³

4.4. Recommendations for stakeholders

The findings of this review point to several actionable recommendations for different stakeholder groups engaged in mathematics teacher education and the integration of IoT with artful approaches.

For teachers, professional development should emphasize not only the technical use of IoT tools but also their creative and pedagogical integration. Teachers are encouraged to design classroom activities that connect IoT data with mathematical modeling, visualization, and esthetic exploration. Embedding artful thinking into instructional practice can foster both conceptual understanding and student engagement.

For administrators, institutional support is essential to sustain innovative practices. This includes providing access to IoT infrastructure, ensuring reliable technical support, and creating opportunities for collaborative experimentation across departments. Administrators can also establish incentives and recognition systems that encourage faculty to integrate interdisciplinary, creativity-oriented approaches into their teaching.

For policymakers, curriculum frameworks should explicitly recognize the potential of IoT to promote interdisciplinary and creative learning in mathematics education. Policy initiatives can support pilot programs, fund longitudinal and cross-cultural studies, and allocate resources to reduce disparities in access to emerging technologies. By embedding creativity and technological fluency within national and regional education strategies, policymakers can align IoT integration with broader goals such as the SDGs, particularly SDG 4 (Quality Education) and SDG 9 (Innovation and Infrastructure).

Collectively, these recommendations highlight that successful implementation of IoT and artful approaches in mathematics teacher education requires coordinated action across classroom, institutional, and policy levels.

4.5. Identified gaps in the reviewed literature and future research directions

Although existing research demonstrates the promise of artful IoT integration in mathematics education, critical gaps remain. These include a lack of longitudinal studies, limited cross-cultural and interdisciplinary investigations, and the absence of robust assessment tools. Addressing these gaps is essential to strengthening both research and practice in this emerging field. The gaps include:

- Limited longitudinal and large-scale studies: The majority of reviewed studies employed small-scale, short-term interventions, highlighting the need for longitudinal research to assess the sustained impacts of artful IoT integration.¹³⁴ Long-term studies could illuminate how creative pedagogies influence teaching practices, student outcomes, and professional identity over time.¹³⁵
- Insufficient cross-cultural and interdisciplinary investigations: Current research seldom examines how cultural differences influence the integration of artful IoT practices in mathematics education.¹³⁶ In addition, there is a lack of interdisciplinary collaborations between educators, technologists, and artists. Expanding the cultural and disciplinary reach of future studies will enhance understanding and promote more tailored, inclusive pedagogical strategies.¹³⁷

- Lack of robust assessment frameworks for creative mathematical learning: A significant gap remains in the availability of validated assessment tools capable of measuring creativity, interdisciplinary reasoning, and esthetic appreciation within mathematical learning contexts.¹³⁸ Developing creative assessment models is critical for capturing the full scope of learning outcomes associated with artful IoT integration.^{139,140}

In response to these gaps, future research must prioritize long-term studies, culturally responsive models, and the development of creative assessment frameworks. Advancing these areas will enhance the sustainability, inclusivity, and impact of artful IoT practices in mathematics teacher education. The details are as follows:

- Investigating long-term impacts of artful IoT experiences: Future research must investigate the longitudinal effects of artful IoT experiences on mathematics teaching practices, professional development, and student learning outcomes.¹⁴¹⁻¹⁴³
- Developing culturally responsive artful IoT models: Researchers should focus on developing culturally responsive artful IoT models that reflect diverse student populations, thereby promoting inclusivity in mathematics education.¹⁴⁴⁻¹⁴⁶
- Creating and validating creative assessment tools: There is an urgent need to create and validate assessment tools capable of authentically measuring creative mathematical inquiry and interdisciplinary integration.¹⁴⁷⁻¹⁴⁹

4.6. Limitations of the review

While this systematic review offers a comprehensive synthesis of research at the intersection of IoT technologies, artful thinking, and mathematics teacher education, several limitations should be acknowledged. First, the review was restricted to English-language, peer-reviewed studies published between 2010 and 2025. This exclusion of studies in other languages or gray literature, such as dissertations, reports, and conference proceedings, may have introduced language and publication bias, limiting the diversity of global perspectives represented.

Second, the included studies exhibited substantial methodological heterogeneity, ranging from qualitative case studies to quasi-experimental and mixed-methods designs. Due to this diversity, a formal meta-analysis was not feasible. The synthesis, therefore, emphasized thematic aggregation, which provides meaningful insights but does not allow for statistical generalization. Findings should thus be interpreted with awareness of the differences in study design, sample size, and context across the literature.

Third, although the MMAT was applied systematically to assess methodological quality, the diversity of research designs still posed challenges in ensuring consistent evaluation. To enhance transparency, additional criteria were incorporated, including clarity of reporting, integration of creativity within study design, and explicit alignment with mathematics teacher education. Future reviews may strengthen comparability by complementing MMAT with other standardized appraisal frameworks that capture domain-specific considerations.

Finally, the relative novelty of research combining artful thinking with IoT in mathematics teacher education presents an inherent limitation. Much of the existing literature consists of exploratory or small-scale studies rather than longitudinal or large-scale investigations. As a result, conclusions about long-term effects on preservice teachers' professional identity, pedagogical competencies, and student learning outcomes remain preliminary. Continued empirical research, particularly longitudinal and cross-cultural studies, will be essential for advancing and validating the insights generated in this emerging field.

5. Conclusion

5.1. Summary of key insights

This systematic review explored the intersections of IoT technologies, artful thinking, and mathematics teacher education, synthesizing findings from 77 selected studies published between 2010 and 2025. The analysis revealed that integrating artful IoT applications into mathematics teacher preparation fosters transformative educational experiences by promoting creativity, interdisciplinary inquiry, and technological fluency. Specifically, IoT technologies were shown to function as versatile mediators that bridge technical content with esthetic and imaginative engagement, reshaping traditional perceptions of mathematics as a rigid and purely procedural discipline.

Three major conceptual areas emerged from the literature. First, artful conceptualizations of IoT emphasized the role of multisensory learning experiences and the reimagining of mathematics as an interdisciplinary, culturally embedded endeavor. Second, applications of IoT in practice—including sensor-driven installations, wearable technologies, and real-world data interpretation—demonstrated powerful avenues for creative mathematical modeling and experiential learning. Third, innovative and sustainable practices linked IoT integration with broader societal goals such as ecological awareness and sustainable development, highlighting the ethical and civic dimensions of mathematical education.

Despite these promising developments, significant challenges persist. Many studies noted barriers such as

limited access to infrastructure, professional development gaps, cultural resistance to open-ended pedagogies, difficulties in assessing creativity, and ethical concerns regarding data use. These issues underscore the necessity of systemic support structures and cultural shifts within teacher education programs to fully realize the transformative potential of artful IoT integration.

5.2. Contribution to the field

This review makes several substantive contributions to the emerging discourse on technology-mediated creativity in mathematics education. First, it critically advances the argument that existing pedagogical frameworks, such as TPACK, require expansion to explicitly incorporate creativity, esthetic engagement, and sustainability as foundational dimensions. By doing so, it responds to calls in contemporary scholarship for educational models that better prepare future teachers for the complex demands of 21st-century learning environments.

Second, the review situates IoT technologies not merely as tools for technical enhancement but also as cultural and communicative artifacts that mediate rich meaning-making processes, drawing on sociocultural learning theories. The integration of artistic and technological experiences fosters deeper conceptual understanding, intercultural competence, and adaptive thinking skills among preservice mathematics teachers. This perspective enriches the theoretical foundations of teacher education by emphasizing the mediational role of technology in the formation of professional identity and pedagogical practice.

Third, the findings articulate the essential role of sustainability-oriented education in the mathematics curriculum, advocating for a reconceptualization of mathematics as a discipline that must engage with real-world problems related to social justice, environmental stewardship, and innovation. Embedding sustainability, creativity, and interdisciplinary problem-solving into mathematics teacher preparation advances the alignment of education with SDGs (particularly SDG 4 and SDG 9), thereby reinforcing education's responsibility toward global citizenship.

Finally, this review identifies practical recommendations for curriculum development, professional learning, and institutional policy, offering a comprehensive roadmap for stakeholders interested in cultivating technologically literate, creatively agile, and socially responsible mathematics educators.

Acknowledgments

None.

Funding

None.

Conflict of interest

The author declares no conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

As this study is a systematic review of published literature, ethical approval was not required.

Consent for publication

Not applicable.

Availability of data

The data generated or analyzed during this systematic review are derived exclusively from publicly available research articles. All data supporting the findings of this study are included within this published article and its referenced sources.

References

- Otgonbaatar K. Examining mathematical creativity among Mongolian ninth-grade students using a problem-posing approach. *J Educ Pract.* 2020;11(27):72-80.
doi: 10.7176/JEP/11-27-08
- Biçer A, Bicer A, Capraro M, Lee Y. Mathematical connection is at the heart of mathematical creativity. *Creat Theor Res Appl.* 2023;10(1-2):17-40.
doi: 10.2478/ctra-2023-0002
- Hayati P, Mistima M, Mahmud M. The relationship between teachers' self-efficacy and the creative teaching of primary mathematics. *J Educ Soc Res.* 2023;13(5):340.
doi: 10.36941/jesr-2023-0141
- Pratiwi P, Istiyowati L. Simulation and games based learning model for learning mathematics in higher education. *Univ J Educ Res.* 2020;8(9A):16-20.
doi: 10.13189/ujer.2020.082003
- Wadaani M. A proposed model for understanding and supporting creativity and mathematical talent development. *Univ J Educ Res.* 2019;7(9):1917-1925.
doi: 10.13189/ujer.2019.070910
- Mariani A, Ismail Z. The elements of teachers' competency for creative teaching in mathematics. *Int Educ Stud.* 2015;8(13):93.
doi: 10.5539/ies.v8n13p93
- Pazin Fadzil A, Maat S, Mahmud M. A rasch model analysis of the TPACK instrument in the creative teaching of primary mathematics teachers. *Cypriot J Educ Sci.* 2022;17(11):4259-4274.
doi: 10.18844/cjes.v17i11.7792
- Hidayat D, Fitriah F, Mahlil M, Mason J. Factors impacting English teachers' creativity in teaching English as a foreign language in Indonesia. *Stud English Lang Educ.* 2023;10(1):155-173.
doi: 10.24815/siele.v10i1.26145
- Vlasenko K, Achkan V, Chumak O, Lovianova I, Armash T. Problem-based approach to develop creative thinking in mathematics students at teacher training universities. *Univ J Educ Res.* 2020;8(7):2853-2863.
doi: 10.13189/ujer.2020.080712
- Aziza M. An analysis of a teacher's questioning related to students' responses and mathematical creativity in a UK elementary school. *Int Electron J Element Educ.* 2018;10(4):475-487.
doi: 10.26822/iejee.2018438138
- Khalid M, Saad S, Abdul Hamid S, Ridhuan Abdullah M, Ibrahim H, Shahrill M. Enhancing creativity and problem-solving skills through creative problem solving in teaching mathematics. *Creat Stud.* 2020;13(2):270-291.
doi: 10.3846/cs.2020.11027
- Fernández-Cézar R, Solano-Pinto N, Garrido D. Can mathematics achievement be predicted? The role of cognitive-behavioral-emotional variables. *Mathematics.* 2021;9(14):1591.
doi: 10.3390/math9141591
- Tezer M. *The Role of Mathematical Modeling in STEM Integration and Education.* In: George Fomunyan, K. editor. London: IntechOpen; 2020. p. 1-20.
doi: 10.5772/intechopen.88615
- Angraini E, Zubaidah S, Susanto H, Omar N. Enhancing creativity in genetics using three teaching strategies based on the TPACK model. *Eur J Math Sci Technol Educ.* 2022;18(12):em2196.
doi: 10.29333/ejmste/12697
- Utemov V, Masalimova A. Differentiation of creative mathematical problems for primary school students. *Eur J Math Sci Technol Educ.* 2017;13(8):4351-4362.
doi: 10.12973/eurasia.2017.00931a
- Chia Mui A, Mahmud M. Teachers' perception of the suitability of Chinese school year 6 mathematics textbook. *Int J Acad Res Prog Educ Dev.* 2023;12(4):1564.
doi: 10.6007/IJARPED/v12-i4/19677
- Lou S, Chou Y, Shih R, Chung C. A study of creativity in

- CAC2 STEMShip-derived STEM project-based learning. *Eur J Math Sci Technol Educ.* 2017;13(6):2387-2404.
doi: 10.12973/eurasia.2017.01231a
18. Jatisunda M, Suciawati V, Nahdi D. Discovery learning with scaffolding to promote mathematical creative thinking ability and self-efficacy. *Al Jabar J Pendidik Mat.* 2020;11(2):351-370.
doi: 10.24042/ajpm.v11i2.6903
19. Chinangure F, Mapaire L. The integration of technology in teaching and learning of mathematics: The missing link. *Curr J Appl Sci Technol.* 2017;23(6):1-13.
doi: 10.9734/CJAST/2017/36184
20. Zulkifli N, Hamzah M, Razak K. Creative teaching practices among Islamic education lecturers: Influence of gender, age, and teaching experience. *J Cakrawala Pendidik.* 2022;41(2):416-424.
doi: 10.21831/cp.v4i2.40206
21. Tamirrino N, Hendriana H, Hidayat W. Analysis of mathematical creative thinking abilities of high school students in West Bandung Regency. *J Innov Math Learn (JIML).* 2023;6(2):104-112.
doi: 10.22460/jiml.v6i2.15580
22. Kim D, Bae S, Choi S, Kim H, Lim W. Creative character education in mathematics for prospective teachers. *Sustainability.* 2019;11(6):1730.
doi: 10.3390/su11061730
23. Jusoh A, Salleh M, Embong R, Mamat M. The influence of mathematical teacher competency on creative teaching practice. *Int J Acad Res Prog Educ Dev.* 2019;7(4):22-28.
doi: 10.6007/IJARPED/v7-i4/5333
24. Pan C. A painting teaching mode based on STEM theory. *Int J Emerg Technol Learn.* 2018;13(8):159.
doi: 10.3991/ijet.v13i08.9048
25. Sanina Y, Artyukhina M, Dendeberya N, Savadova A, Nasikan I. The use of internet technologies in teaching mathematics to economics undergraduates as a factor in students' professional growth. *Int J Recent Technol Eng.* 2019;8(2):3877-3880.
doi: 10.35940/ijrte.B3078.078219
26. Sulistyawati E, Rofiki I. Ethnomathematics and creativity in the construction of batik based on fractal geometry with GeoGebra. *Int J Teach Learn Math.* 2022;4(1):15-28.
doi: 10.18860/ijtlm.v5i1.10883
27. Catarino P, Nascimento M, Morais E, Campos H, Vasco P. (Breaking the habit: Engineering students' understanding of mathematical creativity. *Eur J Eng Educ.* 2019;44(4):449-460.
doi: 10.1080/03043797.2017.1367760
28. Dhayanti D, Johar R, Zubainur C. (Improving students' critical and creative thinking through realistic mathematics education using geometer's sketchpad. *J Res Adv Math Educ.* 2018;3(1):25-35.
doi: 10.23917/jramathedu.v3i1.5618
29. Haavold P, Sriraman B, Lee K. In: Lerman S, editor. *Creativity in Mathematics Education.* Cham: Springer International Publishing; 2020. p. 145-154.
doi: 10.1007/978-3-030-15789-0_33
30. Hamimi E, Nugraheni D, Ardani S, et al. Development of STEM-based learning media fire detector system (FDS) integrated with blynk iot to improve students' creativity in temperature material. *Int J Interact Mobile Technol.* 2024;18(8):140-147.
doi: 10.3991/ijim.v18i08.48219
31. Ismiati N. Implementing STEAM education in the independent curriculum: Enhancing 21st century skills. *Tadibia Islamika.* 2024;4(1):21-27.
doi: 10.28918/tadibia.v4i1.7238
32. Itqan M, Arrahmani N. (Development of IoT-based mathematics learning media with a problem-based learning approach. *Pendidik Pembelajaran Matematika (PPM).* 2023;1(2):9.
doi: 10.47134/ppm.v1i2.120
33. Simamora R, Ramadhanta S. (Investigating the effects of realistic mathematics education on mathematical creativity through a mixed-methods approach. *Indones J Sci Math Educ.* 2024;7(2):337-354.
doi: 10.24042/ijsme.v7i2.21221
34. Soomro S, Casakin H, Nanjappan V, Georgiev G. (Makerspaces fostering creativity: A systematic literature review. *J Sci Educ Technol.* 2023;32(4):530-548.
doi: 10.1007/s10956-023-10041-4
35. Bampasidis G, Galani A, Koutromanos G. (Developing pre-service teachers' STEM skills with Raspberry Pi activities. In: Papadakis S, Kalogiannakis M, editor. *Handbook of Research on Modern Educational Technologies, Applications, and Management.* United States: IGI Global; 2021. p. 327-351.
doi: 10.4018/978-1-7998-6717-3.ch013
36. Chamberlin S, Latonio R, Fox R. Creativity and mathematics education. In: Katz-Buonincontro J, Kettler T, editor. *The Oxford Handbook of Creativity, Innovation, and Entrepreneurship.* Oxford: Oxford University Press; 2025. p. 545-558.
doi: 10.1093/oxfordhb/9780197698181.013.0029
37. Hamid N, Kamarudin N. Assessing students' mathematics achievement and mathematical creativity using the mathematical creative approach: A quasi-experimental study. *Asian J Univ Educ.* 2021;17(2):100.

- doi: 10.24191/ajue.v17i2.13399
38. Hoth J, Kaiser G, Busse A, Döhrmann M, König J, Blömeke S. Professional competences of teachers for fostering creativity and supporting high-achieving students. *ZDM*. 2017;49(1):107-120.
doi: 10.1007/s11858-016-0817-5
 39. Kuchkarova A. The importance of GeoGebra in enhancing students' learning of mathematics at schools. *Actual Prob Hum Soc Sci*. 2023;3(S/5):278-283.
doi: 10.47390/SPI1342V3SI5Y2023N40
 40. Mamatnabiyev Z, Chronis C, Varlamis I, Zhaparov M. Development of an educational robot for exploring the internet of things. *Int J Adv Comput Sci Applic*. 2024;15(4):1197.
doi: 10.14569/IJACSA.2024.01504120
 41. Mamazhanovich I. *Fostering a Creative Personality in Education*. Zenodo Preprint; 2022.
doi: 10.5281/zenodo.5842507
 42. Mariani D, Mustaji M, Dewi U. Literature study: The effect of the problem-based learning model assisted by the flipped classroom on mathematical creative thinking ability. *J Pendidik Indones*. 2025;6(1):75.
doi: 10.59141/japendi.v6i1.6668
 43. Nilimaa J. New examination approach for real-world creativity and problem-solving skills in mathematics. *Trends High Educ*. 2023;2(3):477-495.
doi: 10.3390/higheredu2030028
 44. Suwastika N, Adam Y, Pahlevi R, Masrom M. Math balance aids based on internet of things (IoT) for arithmetic operational learning. *Int J Adv Comput Sci Applic*. 2022;13(8):215.
doi: 10.14569/IJACSA.2022.0130826
 45. Berikzhanovna G. Implementing the educational program based on the project. *Euras Sci Rev Int Peer Rev Multidiscip J*. 2025;1(3):2214-2226.
doi: 10.63034/esr-384
 46. Biçer A. A systematic literature review: Discipline-specific and general instructional practices fostering mathematical creativity of students. *Int J Educ Math Sci Technol*. 2021;9(2):252-281.
doi: 10.46328/ijemst.1254
 47. Bishara S. The cultivation of self-directed learning in teaching mathematics. *World J Educ Technol Curr Issues*. 2021;13(1):82-95.
doi: 10.18844/wjet.v13i1.5401
 48. Firmender J, Dilley A, Amspaugh C, Field K, LeMay S, Casa T. Beyond doing mathematics: Engaging talented students in mathematically creative writing. *Gifted Child Today*. 2017;40(4):205-211.
doi: 10.1177/1076217517722180
 49. Juliantara K, Astawa I, Ardana I. STEM-based learning module oriented towards Balinese ethnomathematics to enhance students' creative mathematical thinking abilities. *J Pedagog Pembela*. 2024;7(2):262-269.
doi: 10.23887/jp2.v7i2.83930
 50. Kozłowski J, Si S. Mathematical creativity: A vehicle to foster equity. *Think Skills Creat*. 2019;33:100579.
doi: 10.1016/j.tsc.2019.100579
 51. Lee J, Heo H. Research on development and application of convergence education program using aperiodic tiling. *Korean Soc Educ Stud Math School Math*. 2024;26(1):1-28.
doi: 10.57090/sm.2024.03.26.1.1
 52. Paneva-Marinova D, Pavlov R, Luchev D, Ruseva M, Bontchev B. The first information day: Serious games as contemporary tools for new educational applications. *Dig Present Preserv Cul Sci Heritage*. 2017;7:283-286.
doi: 10.55630/dipp.2017.7.30
 53. Samritin S, Rizkayati A, Safitri I, Muqaddimah C. Assessing the correlation between creative thinking and mathematics learning success: A meta-analytical perspective. *Indones J Educ Res Rev*. 2024;7(3):630-642.
doi: 10.23887/ijerr.v7i3.80331
 54. Xayrullayevna K. Teaching mathematics interactively: Practices and innovative approaches. *Int J Pedagog*. 2024;4(12):124-126.
doi: 10.37547/ijp/Volume04Issue12-25
 55. Akar Ş. *Fostering Mathematical Giftedness and Creativity Through Measurement*. United States: Akademisyen; 2024.
doi: 10.37609/akya.3403
 56. Poudel M. Empowering students through a self-directed learning pedagogy in mathematics education. *CANA*. 2024;31(1):238-252.
doi: 10.52783/cana.v31.409
 57. Wahyuni Y, Fauzan A, Yerizon Y, Arnawa I, Irfan D, Rasli A. Enhancing creative mathematical thinking with GeoGebra: A comparative study of secondary school students. *Salud Ciencia Tecnol*. 2025;5:1435.
doi: 10.56294/saludcyt20251435
 58. Applebaum M. Cultivating creative minds: An online math course's impact on Chinese students during the COVID-19 pandemic. *Contemp Math Sci Educ*. 2025;6(1):ep25003.
doi: 10.30935/conmaths/15884
 59. Applebaum M. Fostering creative and critical thinking through math games: A case study of Bachet's game. *Eur J Sci Math Educ*. 2025;13(1):16-26.

- doi: 10.30935/scimath/15825
60. Arnellis A, Syarifuddin H, Ismail R. Optimizing students' mathematical critical and creative thinking skills through the flip-A-team model with e-learning. *Al-Jabar J Pendidik Matem.* 2023;14(1):133-140.
doi: 10.24042/ajpm.v14i1.16904
61. Bardhan R. Pedagogical framework on the integration of platonic solids in 2020s STEM curricula. *Towards Excell.* 2024;16:227-236.
doi: 10.37867/TE160318
62. Laili A, Istikomah I. Impact of differentiated learning management on enhancing students' creative thinking in mathematics. *AL-ISHLAH J Pendidik.* 2024;16(3):4108-4117.
doi: 10.35445/alishlah.v16i3.4807
63. Vasconcelos L. *Fostering Creativity in Education.* [ResearchGate Preprint]; 2017.
doi: 10.13140/rg.2.2.25607.70568
64. Yaftian N. A conceptual model of the role of the instructor in fostering students' mathematical creativity. *J Res Adv Math Educ.* 2023;8(2):112-122.
doi: 10.23917/jramathedu.v8i2.3136
65. Bruhn S, Lüken M. A framework to characterize young school children's individual mathematical creativity: An integrative review. *Asian J Math Educ.* 2023;2(1):116-144.
doi: 10.1177/27527263231163267
66. Connolly C, Gorman SO, Hall T, Hijón-Neira R. Preservice teacher perceptions of integrating maker-centered learning into mathematics education programs. *Univ Tarracon Rev Cièn Educ.* 2020;1(3):50.
doi: 10.17345/ute.2020.3.2778
67. Jalil A, Siew N. Validity and reliability of behavioral instruments for fostering creativity of secondary school mathematics teachers using the Rasch measurement model. *Int J Educ Psychol Counsel.* 2022;7(45):386-401.
doi: 10.35631/IJEPC.745030
68. Metu C, Ugwuanyi C, Nwoye N, Odo I, Nwachukwu W. Unlocking students' areas of difficulties in mathematics through teachers' creativity-fostering behaviors. *Int J Res Innov Soc Sci.* 2023;7(9):389-396.
doi: 10.47772/ijriss.2023.70932
69. Qian B, Cheng H. C-STEM studio: A solution for learning computing and STEM topics with robotics and embedded systems. In: *Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* United States: American Society of Mechanical Engineers; 2017.
doi: 10.1115/DETC2017-68362
70. Supandi S, Suyitno H, Sukestiyarno Y, Dwijanto D. Learning barriers and student creativity in solving math problems. *J Phys Conf Ser.* 2021;1918(4):042088.
doi: 10.1088/1742-6596/1918/4/042088
71. Šimon J, Gogolák L. Development of an IoT-based 3D printed mobile robot platform for training mechatronics engineering students. *Anal Tech Szegedinens.* 2024;18(1):18-30.
doi: 10.14232/analecta.2024.1.18-30
72. Bezerra W, Gontijo C, Fonseca M. Fostering mathematical creativity in the classroom through feedbacks. *Acta Sci.* 2021;23(2):88-112.
doi: 10.17648/acta.scientiae.6213
73. Huê P, Hoà N, Trang T. The design of a STEM-themed model for a smart home integrated with AI and IoT technologies for high school students. *East Afr Scholar J Eng Computer Sci.* 2025;8(2):30-38.
doi: 10.36349/easjecs.2025.v08i02.003
74. Jorge A, Lourenço M, Maia M. Fostering creativity in design education. In: *Creativity Studies in Design and Engineering Education.* New Delhi: Council on Technology Teacher Education; 2024. p. 796-811.
doi: 10.1007/978-3-031-77566-6_58
75. Kelechi E, Nnaji CO. The role of augmented reality (AR) in interactive learning for children. *ICISTech.* 2024;4(1):180-185.
doi: 10.62951/icistech.v4i1.139
76. Makuseva T, Kayumova A, Makusev O. Fostering creativity in university education. *Bull Sci Pract.* 2025;11(4):392-399.
doi: 10.33619/2414-2948/113/52
77. Monahan C, Munakata M, Vaidya A. Creativity as an emergent property of a complex educational system. *N J Complex Syst.* 2019;1(1):4.
doi: 10.22191/nejcs/vol1/iss1/4
78. Qizi M. Methodology for organizing independent work of students in mathematics in primary schools. *Am J Soc Sci Educ Innov.* 2021;3(1):374-377.
doi: 10.37547/tajssei/volume03issue01-70
79. Unterfrauner E, Addis A, Fabian C, Yeomans L. STEAM education: The claim for socially innovative practices. *Creat Educ Innov Rev.* 2024;8(8):71-98.
doi: 10.7203/CREATIVITY.8.29743
80. Chacón R, Posada H, Toledo Á, Gouveia M. Development of IoT applications in civil engineering classrooms using mobile devices. *Comput Applic Eng Educ.* 2018;26(5):1769-1781.
doi: 10.1002/cae.21985
81. Suyitno A. Growth of student mathematical creativity as part of 4C competence for entering the 21st century. *J Phys Conf Ser.* 2020;1567(2):022100.
doi: 10.1088/1742-6596/1567/2/022100

82. Anita IW. Implementation of project-based learning to foster students' mathematical creative thinking ability. *J Penelitian Pembelajaran Mat*. 2017;10(1):125-131.
doi: 10.30870/jppm.v10i1.1287
83. Munaji M, Rohaeti T, Mutadi M, Sumliyah S, Kodirun K. A literature review of flexibility in interactive mathematics classrooms: The role of teachers and students. *J Educ Learn*. 2025;19(2):597-605.
doi: 10.11591/edulearn.v19i2.21501
84. Nadiroh I. Implementation of co-op co-op learning using Wingeom media to improve students' reasoning in Islamic elementary school education. *Tafáqquh J Penelit Kajian Keislaman*. 2016;4(1):12-29.
doi: 10.52431/tafaqquh.v4i1.52
85. Annet K. The effects of arts education on academic achievement. *NIJCIAM*. 2024;5(3):14-17.
doi: 10.59298/NIJCIAM/2024/5.3.14170
86. Pasaribu R, Ananda N, Alwahab P, Saputra M, Putra J. The impact of implementing the open-ended learning model on enhancing students' mathematical creative thinking skills: A systematic literature review. *J Prinsip Pendidikan Mat*. 2024;7(2):169-181.
doi: 10.33578/prinsip.v7i2.278
87. Sekinaeva B. Use of multimedia resources in the practice of teaching mathematics. *Sci Notes Orel State Univ*. 2023;2(99):302-306.
doi: 10.33979/1998-2720-2023-99-2-302-306
88. Zuhri S. Management of religious education learning in the era of Industry 4.0. *Geneol PAI J Pendidik Agama Islam*. 2020;7(1):76-86.
doi: 10.32678/geneologipai.v7i1.2656
89. Milner-Bolotin M, Zazkis R. Unleashing creativity in STEM teacher education through scripting task pedagogy. *Fut Educ Res*. 2025;3(1):13-27.
doi: 10.1002/fer3.52
90. Samaniego M, Usca N, Salguero J, Quevedo W. Creative thinking in art and design education: A systematic review. *Educ Sci*. 2024;14(2):192.
doi: 10.3390/educsci14020192
91. Seftiana G, Lestari N, Isnawan M, Rusmayadi M. Utilization of GeoGebra software in mathematics learning: A systematic literature review. *Poly Int J Math Educ*. 2024;2(1):156-163.
doi: 10.59965/pijme.v2i1.95
92. Yang B. From STEM to STEAM: The connections and fostering of creativity in STEAM. *Lect Notes Educ Psychol Public Media*. 2023;2(1):441-446.
doi: 10.54254/2753-7048/2/2022322
93. Saraç A, Özden N. Adapting to the industry 4.0 era: The role of innovative skills in education. In: Kumar R, Ong E, Anggoro S, Toh T, editors. *Handbook of Research on Emerging Trends and Technologies in Librarianship*. United States: IGI Global; 2024. p. 95-153.
doi: 10.4018/979-8-3693-3699-1.ch004
94. Stylianidou F, Glauert E, Rossis D, Havu-Nuutinen S. Creative little scientists' project: Mapping and comparative assessment of early years science education policy and practice. In: Papadouris N, Hadjigeorgiou A, Constantinou C, editors. *Insights from Research in Science Teaching and Learning*. Cham: Springer International Publishing; 2016. p. 201-220.
doi: 10.1007/978-3-319-20074-3_14
95. Utami A, Sandi A, Lutfi A. Fostering creative thinking and creative products through the Stream approach. *J Inovasi Pendidikan IPA*. 2025;11(1):248-258.
doi: 10.21831/jipi.v11i1.71527
96. Gorev P, Telegina N, Karavanova L, Feshina S. Puzzles as a didactic tool for developing the mathematical abilities of junior schoolchildren in basic and additional mathematics education. *Euras J Math Sci Technol Educ*. 2018;14(10):em1602.
doi: 10.29333/ejmste/93675
97. Maro S, Kondoro A, Mtebe J, Proctor J, Komba A, Haßler B. Exploring the feasibility of deploying technology-enhanced school-based teacher continuous professional development in internet-limited environments in Tanzania. *Int Rev Res Open Distribut Learn*. 2024;25(2):60-76.
doi: 10.19173/irrodl.v25i2.7428
98. Setiawan A, Suwahyo S, Darsono F, et al. Design of a wireless engine diagnostic tool with Raspberry Pi for vocational education teacher candidates. *Vanos J Mech Eng Educ*. 2023;8(1):78-87.
doi: 10.30870/vanos.v8i1.19097
99. Winarko G. Project-based learning with Scratch to improve students' creative thinking ability: Systematic literature review. *Griya J Math Educ Appl*. 2024;4(2):190-196.
doi: 10.29303/griya.v4i2.440
100. Daskolia M, Kolovou A, Kynigos C. Social Creativity in Designing Digital Resources Interweaving Math with Environmental Education: The Case Study of the Climate Change C-Book. In: *Proceedings of the 8th International Conference on Computer Supported Education (CSEDU 2016)*. Vol. 1. 2016. p. 134-143.
doi: 10.5220/0005810101340143
101. Sakabe Y, Ayedoun E, Tokumaru M. Meshing Minds: Bridging the Gap between Creativity and IoT Programming Through Collaborative Mixed Reality. In: *International Conference on Computers in Education*; 2024.

- doi: 10.58459/icce.2024.4831
102. Syutaridho S, Ramury F, Nurhijah N. The influence of Indonesia's realistic mathematics education approach on students' creative thinking ability. *J Ilm Ilmu Terapan Univ Jambi*. 2023;7(2):99-111.
doi: 10.22437/jiituj.v7i2.28700
 103. Ritonga L. Challenges and innovations in mathematics education through a multidisciplinary approach to foster critical thinking skills. *Calakan*. 2024;2(2):88-92.
doi: 10.61492/calakan.v2i2.163
 104. Rinke C, Gladstone-Brown W, Kinlaw C, Cappiello J. Characterizing STEM teacher education: Affordances and constraints of explicit STEM preparation for elementary teachers. *School Sci Math*. 2016;116(6):300-309.
doi: 10.1111/ssm.12185
 105. Kannadass P, Hidayat R, Siregar P, Husain A. Relationship between computational and critical thinking towards modeling competency among preservice mathematics teachers. *TEM J*. 2023;12(3):1370-1382.
doi: 10.18421/TEM123-17
 106. Şenel M, Döş B. Exploring the integration of artful thinking as an innovative approach to foster critical thinking skills. *Int J Mod Educ Stud*. 2024;8(1):24-48.
doi: 10.51383/ijonmes.2024.361
 107. Erümit A, Özmen S, Cebeci H. The impact of using various programming tools on pre-service teachers' self-efficacy beliefs and computational thinking skills. *Int J Euras Soc Sci*. 2025;16(59):80-97.
doi: 10.70736/ijoess.540
 108. Siska Pramasdyahsari A, Puspita Arum J, Esti Utami R, Prasad Pant B. Construct analysis of STEAM mitigation activities to foster creativity. *Prismatik J Pendidik Riset Mat*. 2024;7(1):1-13.
doi: 10.33503/prismatika.v7i1.126
 109. Naufal M, Ihsan H, Samsuddin A, Zainal Z, Ashari N, Hassan M. Evaluating the geometric thinking levels of Generation Z pre-service mathematics teachers in Indonesia. *Int J Eval Res Educ*. 2025;14(2):918.
doi: 10.11591/ijere.v14i2.32365
 110. Urban M, Vasiļevska D, Abchynets A. Visual models as a means of teaching in primary mathematics education: Problems of teacher training. *Acta Prosper*. 2021;12:193-202.
doi: 10.37804/1691-6077-2021-12-193-202
 111. Mohr S, Santagata R. Changes in pre-service teachers' beliefs about mathematics teaching and learning during teacher preparation and effects of video-enhanced analysis of practice. *Orbis Schol*. 2018;9(2):103-117.
doi: 10.14712/23363177.2015.82
 112. Jao L, Proietti M, Kobiela M. Examining the development of a transdisciplinary collaboration. In: *Transdisciplinary Research in Mathematics Education*. Berlin: Springer; 2017. p. 255-275.
doi: 10.1007/978-3-319-63624-5_13
 113. Alzubaidi I. Effectiveness of a proposed training program based on the Caffarella model in developing computational thinking teaching skills and financial culture among middle school mathematics teachers. *J Posthumanism*. 2025;5(3):358-390.
doi: 10.63332/joph.v5i3.744
 114. Kurniati D, Trapsilasiwi D, As'ari A, Basri H, Osman S. Prospective mathematics teachers' critical thinking disposition in designing cognitive and psychomotor assessment instruments. *Tadris J Keguruan Ilmu Tarbiyah*. 2022;7(1):1-14.
doi: 10.24042/tadris.v7i1.11263
 115. Vale I, Barbosa A. Mathematics and art: Ideas to use in teacher education. *Arts Commun*. 2025:6487.
doi: 10.36922/ac.6487
 116. Adam M. The effectiveness of a training unit on habits of mind in developing mathematical achievement, creative thinking, and attitudes towards mathematics among female university students. *J Math Educ*. 2017;20(7):47-124.
doi: 10.21608/armin.2017.81643
 117. Namakshi N, Warshauer H, Strickland S, McMahon L. Investigating preservice teachers' assessment skills: Relating aspects of teacher noticing and content knowledge for assessing student thinking in written work. *School Sci Math*. 2022;122(3):142-154.
doi: 10.1111/ssm.12522
 118. Yurt E. Teachers' views and experiences regarding acquiring analytical thinking skills in the middle school mathematics curriculum. *Int J Soc Educ Sci*. 2022;4(4):599-619.
doi: 10.46328/ijonses.475
 119. Maharani S, Nusantara T, As'ari A, Qohar A. Exploring the computational thinking of our preservice mathematics teachers of lesson plans. *J Phys Conf Ser*. 2021;1783(1):012101.
doi: 10.1088/1742-6596/1783/1/012101
 120. Turner E, Drake C. A review of research on prospective teachers' learning about children's mathematical thinking and cultural funds of knowledge. *J Teach Educ*. 2016;67(1):32-46.
doi: 10.1177/0022487115597476
 121. Armah R. Geometric thinking of prospective mathematics teachers: Assessing the foundation built by undergraduate education in Ghana. *Teach Educ Curr Stud*. 2024;9(2):40-51.
doi: 10.11648/j.tecs.20240902.12
 122. Jurdak M. Integrating the sociocultural and the sociopolitical

- in mathematics education. In: Jurdak M, Vithal R, editor. *Sociopolitical Dimensions of Mathematics Education*. Cham: Springer International Publishing; 2018. p. 15-33.
doi: 10.1007/978-3-319-72610-6_2
123. Jin S. A study on mathematics lesson design of prospective elementary school teachers by using latent profile analysis. *Korean Soc Educ Stud Math J Educ Res Math*. 2022;32(2):103-124.
doi: 10.29275/jerm.2022.32.2.103
124. Rasool Siddiqui G, Rashid K. Relationship between mathematical thinking of teachers and academic achievement of secondary school students. *Pak J Soc Res*. 2023;5(1):398-403.
doi: 10.52567/pjsr.v5i01.1019
125. Ключко О. Development of critical thinking among future computer science and mathematics teachers using artificial intelligence tools. *Mod Inform Technol Innov Methodol Educ Prof Train Methodol Theory Exp Prob*. 2024;72:14-26.
doi: 10.31652/2412-1142-2024-72-14-26
126. Kandemir M. Examination of reflective thinking tendency levels of elementary mathematics and classroom teacher candidates based on some variables. *NWSA Acad J*. 2015;10(4):253-275.
doi: 10.12739/NWSA.2015.10.4.1C0646
127. Zhang X, Yang Z. Study on pre-service mathematics teachers' mathematical critical thinking ability in China: A review. *Asian J Educ Soc Stud*. 2022;27:19-26.
doi: 10.9734/ajess/2022/v27i230651
128. Al-Rubaie M. The role of mathematics teachers in developing creative thinking skills. *J Arts Literatu Hum Soc Sci*. 2020;57:188-199.
doi: 10.33193/JALHSS.57.2020.188
129. Setiawati E. Relevance of technical substantive training for mathematics teachers to creative mathematical thinking ability. *Tatar Pasund J Diklat Keagam*. 2021;15(1):90-108.
doi: 10.38075/tp.v15i1.212
130. Coşkun S. Animations and depictions as tools to improve preservice elementary teachers' noticing of students' mathematical thinking. *J Pedagog Res*. 2024;8:192.
doi: 10.33902/jpr.202424231
131. Nurpeysov K, Nurgaby D. A model of the process for forming the readiness of future mathematics teachers to teach schoolchildren in the context of the PISA-2021 concept. *Sci Herald Uzhhorod Univ Ser Phys*. 2024;56:1240-1250.
doi: 10.54919/physics/56.2024.124vt0
132. Rabeh S, Abdelsadeq A. The effect of using the SWOM strategy on developing productive thinking skills and mathematical confidence among fifth-grade primary students. *J Math Educ*. 2022;7:158-205.
doi: 10.21608/armin.2022.270367
133. Furness J, Cowie B, Cooper B. Scoping the meaning of "critical" in mathematical thinking for initial teacher education. *Policy Fut Educ*. 2017;15(6):713-728.
doi: 10.1177/1478210317719778
134. Dobrick A, Fattal L. Exploring exemplars in elementary teacher education. *Soc Stud Res Pract*. 2018;13(1):72-83.
doi: 10.1108/SSRP-07-2017-0039
135. Jung E, Zhang Y, Chiang J. Teachers' mathematics education and readiness beliefs, and kindergarteners' mathematics learning. *Int J Educ Math Sci Technol*. 2019;7:22-39.
doi: 10.18404/ijemst.552416
136. Kooloos C, Oolbekkink-Marchand H, Van Bove S, Kaenders R, Heckman G. Making sense of student mathematical thinking: The role of teacher mathematical thinking. *Educ Stud Math*. 2022;110(3):503-524.
doi: 10.1007/s10649-021-10124-2
137. Pentang J, Caubang M, Tidalgo A, et al. Demystifying the relationship between confidence and critical thinking in mathematics among preservice teachers in the West Philippines. *Eur J Educ Res*. 2023;12(4):1743-1754.
doi: 10.12973/eu-jer.12.4.1743
138. Muntazhimah M, Wahyuni R. The development and validation of a mathematical reflective thinking test for prospective mathematics teachers using the Rasch model. *J Elemen*. 2022;8(1):175-186.
doi: 10.29408/jel.v8i1.3981
139. Rupe K, Borowski R. Supporting preservice elementary teachers in planning for mathematical discussions. In: Kartal O, Popovic G, Morrissey S, editors. *Handbook of Research on Teacher Education and Professional Development*. United States: IGI Global; 2022. p. 136-160.
doi: 10.4018/978-1-7998-9422-3.ch007
140. Foca E. Transformative Learning Through Art Pedagogy: An Innovative Approach to Professional Teacher Training. In: *Proceedings of the International Scientific Conference*. Ion Creangă Pedagogical State University; 2023. p. 342-346.
doi: 10.46727/s.23-06-2023.p342-346
141. Al-Malak M. A proposed program based on storytelling of mathematical autobiographies for developing reflective thinking and professional identity among preservice mathematics teachers. *J Math Educ*. 2021;24(6):7-61.
doi: 10.21608/armin.2021.186828
142. Mykhaylenko L. Criteria and indicators of methodological competence of the future teacher of mathematics in the process of development of logical thinking of students. Academic Notes Series. *Acad Notes Ser Pedagog Sci*.

- 2020;1(191):120-123.
doi: 10.36550/2415-7988-2020-1-191-120-123
143. Sari D, Suhendra S, Nurlaelah E. How prospective mathematics teachers perform computational thinking tasks: An analysis of prior knowledge. *Hipoten J Math Soc*. 2024;6(1):31-43.
doi: 10.18326/hipotenusa.v6i1.1908
144. Smith C, Bretscher N. Designing teacher education for pre-university mathematics: Articulating and operationalizing pedagogic messages. *Teach Math Application Int J IMA*. 2018;37(2):84-97.
doi: 10.1093/teamat/hry008
145. Sulaieva N. Training future teachers for developing students' creative thinking in art classes in secondary education institutions. *Sour Pedagog Skills*. 2024;33:201-206.
doi: 10.33989/2075-146x.2024.33.310080
146. Dietrich S, Hulan N, Kirby G, Evans S. Clinically based models of teacher preparation. *Educ Renaiss*. 2016;4(1):19-26.
doi: 10.33499/edren.v4i1.84
147. Al-Maliki A. The degree of use of electronic thinking maps strategy by middle school mathematics teachers and obstacles to their use from their point of view. *J Umm Al-Qura Univ Educ Psychol Sci*. 2024;16(3):494-509.
doi: 10.54940/ep96241067
148. Mellawaty M, Taufan M. LMS-Google Classroom digital platform: Impact on the critical thinking ability, self-concept, and mathematics anxiety of preservice mathematics teachers during the COVID-19 pandemic in Indonesia. *J Phys Conf Ser*. 2021;1783(1):012126.
doi: 10.1088/1742-6596/1783/1/012126
149. Meylani R. Transforming education with the internet of things: A journey into smarter learning environments. *Int J Res Educ Sci*. 2024;10(1):161-178.
doi: 10.46328/ijres.3362