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Interactive GUIs and 3D Visualization in Computational Mathematics Education: A Systematic Literature Review

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Abstract

Graphical User Interfaces (GUIs) and 3D visualization can support computational mathematics learning by making abstract, spatial, and dynamic concepts more accessible. However, evidence concerning their pedagogical applications, reported outcomes, and implementation challenges remains fragmented across technologies and educational contexts. This systematic literature review identifies, classifies, and synthesizes research on GUI- and 3D-supported computational mathematics education. Open-access publications written in English or Indonesian and indexed in Scopus, the Directory of Open Access Journals, and Google Scholar between 2015 and 2025 were examined using a PRISMA-informed selection process. Of the 28,563 records initially identified, 1,123 were retained for bibliometric and keyword co-occurrence analysis, while 31 studies met the full eligibility criteria and were included in the qualitative synthesis. The included studies were analyzed through thematic coding, cross-study comparison, and narrative synthesis. Bibliometric mapping identified four major clusters: technology-supported learning environments; visualization, GUI, and user interaction; simulation and advanced computational methods; and datasets, images, and predictive models. Across the included studies, GUI and 3D visualization were generally associated with reported improvements in conceptual understanding, learning motivation, engagement, and interaction with mathematical representations. Nevertheless, their educational value depended on usability, instructional scaffolding, curriculum alignment, teacher readiness, and technological accessibility. The findings provide design-oriented guidance for educators and developers and highlight the need for rigorous research in non-geometry domains, standardized evaluation methods, and integrated pedagogical frameworks for computational mathematics education.

Keywords: Computational Mathematics Education; Graphical User Interface; 3D Visualization; Interactive Learning Tools; Systematic Literature Review

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INTRODUCTION

Computational mathematics has become an important component of contemporary STEM education because it enables learners to formulate mathematical models, conduct numerical analyses, and investigate complex systems through simulation. In physics, engineering, computer science, and related disciplines, computational approaches allow students to connect mathematical reasoning with realistic problems that may be difficult to examine analytically or experimentally (Li, 2024; Negahban, 2024; Gutiérrez et al., 2022; Zhang et al., 2023). In this study, computational mathematics education refers to the use of mathematical modeling, numerical methods, programming, simulation, and interactive technologies to support mathematical understanding. Computational Thinking (CT), including abstraction, decomposition, modeling, and algorithmic reasoning, is treated as a related learning outcome rather than as a term synonymous with computational mathematics (Mukhibin & Juandi, 2023; Cabrera et al., 2023; Manea et al., 2025).

Despite its educational importance, computational mathematics remains challenging because many of its concepts are abstract, dynamic, spatial, or multidimensional. Students may have difficulty interpreting differential-equation systems, spatial transformations, numerical algorithms, and relationships among mathematical variables when instruction relies primarily on symbolic notation or static two-dimensional representations (Apriyani, 2022; Mukhibin & Juandi, 2023). Simulation-based learning can improve engagement and conceptual learning, but its benefits depend on how learners manage the associated cognitive and affective demands (Magana et al., 2022). These difficulties create a need for learning environments that make computational processes observable and allow students to explore mathematical relationships interactively.

Graphical User Interfaces (GUIs) address this need by connecting visual, symbolic, numerical, and computational representations within a single interactive environment. Through buttons, sliders, menus, graphical outputs, and manipulable objects, students can change parameters, observe corresponding results, and compare multiple representations of the same mathematical relationship. GeoGebra exemplifies this integration by combining modeling, visualization, and programming, thereby enabling learners to manipulate mathematical objects in real time and coordinate visual and symbolic reasoning (Ziatdinov & Valles, 2022). Other digital environments, including Microsoft Mathematics and MATLAB-based learning media, similarly support interactive exploration of calculus, modeling, and mathematical connections (Rabi et al., 2022; Putra et al., 2022). Putra et al. (2022), for example, reported a validity score of 86.5% and an average student-effectiveness score of 85.84% for MATLAB GUI-based mathematics learning media. GeoGebra-based learning has also been associated with the development of decomposition, algorithmic reasoning, abstraction, and spatial understanding (Sitorus & Yahfizham, 2022; Silfanus Jelatu et al., 2019; Tyaningsih et al., 2025).

Three-dimensional visualization extends these affordances by representing spatial structures and dynamic relationships that may be difficult to communicate through two-dimensional diagrams. Augmented reality, virtual reality, 3D printing, and other manipulable representations allow learners to rotate, transform, construct, and examine mathematical objects from multiple perspectives. Such interactions have been reported to support spatial visualization, geometric reasoning, and mental representation (Medina Herrera et al., 2019; Ng et al., 2018; Özçakir & Cakiroglu, 2021). Immersive geometry environments and mixed-reality applications likewise illustrate how three-dimensional representations can scaffold understanding of spatial relationships and transformations (Rodríguez et al., 2021; Romero et al., 2023; Pujiastuti et al., 2024). In addition, MATLAB-based visualization has demonstrated the relationship between spatial-visualization skills and vector-calculus problem solving (Amevor et al., 2021).

The benefits of GUI and 3D visualization should nevertheless be interpreted in relation to their design and accessibility. A visual interface may not improve learning when it presents excessive information, requires unfamiliar interactions, or fails to connect visual activity with mathematical explanation. Two-dimensional interfaces may also be insufficient for representing real-time spatial mechanisms and multidimensional relationships, even when they provide useful symbolic and graphical tools (García-García et al., 2025). Moreover, purely graphical systems may remain inaccessible to learners who require tactile, auditory, or other assistive representations (Mukhiddinov & Kim, 2021; Jafri et al., 2022; Shoaib et al., 2023). Beginner learners can also experience difficulty translating symbolic screen representations into meaningful actions in GUI-based environments (Demir, 2021). Therefore, the educational value of these technologies depends on usability, instructional scaffolding, accessibility, and alignment with explicit learning objectives.

Research on GUI, 3D visualization, AR, VR, and CT in mathematics and STEM education has expanded, but the evidence remains distributed across different technologies, disciplines, mathematical topics, and outcome measures. Ahmad and Junaini (2020) identified only 19 eligible studies in their systematic review of AR for mathematics learning. Reviews of CT in mathematics education have documented increasing research activity but have also shown substantial variation in learning tools, instructional strategies, and evaluation methods (Khoo et al., 2022; Mukhibin & Juandi, 2023; Ye et al., 2023). Cevikbas et al. (2023) reviewed 59 studies of AR and VR in mathematics education and found that geometry was the most frequently investigated domain, while the reported advantages and limitations varied across applications. Related systematic evidence also indicates notable use of GUIs and VR in engineering and computational learning, but these technologies are commonly examined separately or within discipline-specific contexts (Giraldo et al., 2023).

Consequently, the main research gap does not arise from an absence of GUI- or visualization-based studies, but from the lack of an integrated synthesis that connects interface design, three-dimensional representation, reported learning outcomes, implementation challenges, and pedagogical requirements in computational mathematics education. Existing studies frequently focus on specific software, immersive environments, spatial tasks, or technical performance, making it difficult to identify consistent patterns across educational levels and mathematical domains. In particular, the literature provides limited integrated guidance on how GUI and 3D visualization should be designed and implemented to support mathematical reasoning and CT rather than functioning only as attractive or technically sophisticated learning media.

Accordingly, this study systematically identifies, classifies, and synthesizes research on the use of GUIs and 3D visualization in computational mathematics learning. It addresses four questions:

(1) What types of GUI and 3D visualization technologies have been used in computational mathematics education?
(2) What cognitive, affective, usability, and Computational Thinking outcomes have been reported?
(3) What technical, pedagogical, and institutional challenges influence their implementation? and
(4) What design principles and future research directions can support their effective and sustainable integration? By answering these questions, the review aims to

provide an empirical basis for developing learning tools and pedagogical strategies that are interactive, accessible, and aligned with contemporary computational mathematics learning needs.

METHOD

Research Design and Reporting Framework

This study employed a qualitative Systematic Literature Review (SLR) to identify, classify, and synthesize research on the use of Graphical User Interfaces (GUIs) and 3D visualization in the development, implementation, and evaluation of computational mathematics learning tools. The SLR approach was selected because it enables systematic conceptual mapping and an in-depth examination of research trends, technological approaches, reported learning outcomes, and implementation challenges in computational mathematics education.

The review process was structured according to PRISMA-based reporting principles, particularly the transparent documentation of study identification, screening, eligibility assessment, and final inclusion. Methodological literature in mathematics education and educational technology emphasizes the explicit reporting of the review rationale, objectives, information sources, search procedures, eligibility criteria, study-selection process, and synthesis methods to improve reproducibility and cross-study comparability (Stracke et al., 2023; Ismail et al., 2023; Rocha et al., 2025; Yazdipour et al., 2022; Zuge et al., 2024; Turaga, 2023).

Eligibility Criteria

Studies were included when they met the following criteria: (1) explicitly examined the use of GUI and/or 3D visualization in mathematics or computational learning; (2) focused on the development, implementation, or evaluation of learning tools; (3) addressed learners at the primary, secondary, or higher education level; (4) were published between 2015 and 2025; (5) were written in English or Indonesian; (6) were available through open-access channels; and (7) provided sufficient information about the research methods, implementation process, or reported findings.

Studies were excluded when they: (1) were not relevant to GUI or 3D visualization in an educational context; (2) focused exclusively on technical programming or software development without a learning component; (3) did not address mathematics or computational learning; (4) did not examine the development, implementation, or evaluation of learning tools; (5) were non-scientific publications, such as editorials, commentaries, or opinion papers; or (6) did not provide sufficient methodological information, data, or analytical findings for systematic review.

Information Sources and Search Strategy

Literature searches were conducted in Scopus, the Directory of Open Access Journals (DOAJ), and Google Scholar. The final search in all three databases was completed on 12 August 2025. The search covered publications issued between 2015 and 2025 and was restricted to studies written in English or Indonesian. Open-access availability was verified through database filters or during the screening process.

The search terms represented four principal dimensions of the review: learning tools, graphical user interfaces, 3D visualization, and computational mathematics. Because the databases differed in their indexing structures and search functions, database-specific search expressions and filters were applied. Table 1 summarizes the search strategy used for each information source.

As shown in Table 1, the search strategy was adapted to the technical capabilities of each database while maintaining consistent concepts, publication periods, language restrictions, and access requirements. Transparent reporting of database selection, search terminology, search dates, publication restrictions, study-selection procedures, and data-extraction processes is essential for improving the reproducibility of systematic reviews involving heterogeneous educational research (Yazdipour et al., 2022; Morte-Nadal & Navarro, 2022; Tse et al., 2025; Kühn et al., 2024).

Table 1. Database-Specific Search Strategies and Applied Filters

Database	Search expression or query approach	Applied filters and limitations
Scopus	*TITLE-ABS-KEY (("graphical user interface" OR GUI OR "user interface" OR "interactive interface") AND ("3D visualization" OR "three-dimensional visualization" OR "3D visualisation" OR "augmented reality" OR "virtual reality") AND ("mathematics education" OR "mathematics learning" OR "computational mathematics" OR "computational learning" OR "learning tool" OR "educational technolog"))* AND PUBYEAR > 2014 AND PUBYEAR < 2026**	Publication period: 2015–2025; language: English or Indonesian; open-access publications; search fields: title, abstract, and keywords.
DOAJ	("graphical user interface" OR GUI OR "interactive interface") AND ("3D visualization" OR "three-dimensional visualization" OR "augmented reality" OR "virtual reality") AND ("mathematics education" OR "mathematics learning" OR "computational mathematics" OR "learning tools")	Publication period: 2015–2025; language: English or Indonesian; open-access publications.
Google Scholar	Separate searches were conducted using the following phrase combinations: “graphical user interface” mathematics learning; GUI computational mathematics; “3D visualization” mathematics education; “three-dimensional visualization” mathematics learning; “augmented reality” mathematics education; “virtual reality” computational mathematics; and “interactive learning tools” computational mathematics.	Publication period: 2015–2025; language: English or Indonesian; accessible full text required. Separate phrase searches were used because Google Scholar provides limited support for complex nested Boolean expressions.

Study Selection Process

The study-selection process consisted of four sequential stages: record identification, duplicate removal, title and abstract screening, and full-text eligibility assessment. Screening and data extraction were conducted collaboratively by a six-member research team. Table 2 presents the number of records retained or excluded at each stage of the selection process.

As presented in Table 2, the initial search identified 28,563 records. After 2,147 duplicate records were removed, 26,416 records were screened by title and abstract. This stage excluded 25,293 records and retained 1,123 publications for full-text eligibility assessment. Following full-text assessment, 31 studies met all inclusion requirements. Table 3 presents the reasons for excluding the remaining 1,092 full-text publications.

Table 2. Summary of the Study-Selection Process

Selection stage	n	Description
Records identified	28,563	Open-access records identified through searches in Scopus, DOAJ, and Google Scholar.
Duplicate records removed	2,147	Records appearing more than once across the three databases were removed before screening.
Records screened by title and abstract	26,416	Unique records assessed for topical relevance, educational context, publication type, language, publication period, and full-text accessibility.
Records excluded during title and abstract screening	25,293	Records that did not meet the preliminary eligibility requirements were excluded.
Full-text publications assessed for eligibility	1,123	Potentially relevant publications evaluated using the predetermined inclusion and exclusion criteria.
Full-text publications excluded	1,092	Publications excluded after detailed examination of their research focus, educational context, methodological information, and analytical content.
Studies included in the final qualitative synthesis	31	Studies that met all eligibility requirements and constituted the final review corpus.

Table 3. Reasons for Exclusion During Full-Text Eligibility Assessment

Reason for full-text exclusion	n	Explanation
Not focused on GUI or 3D visualization in an educational context	416	The publication did not examine GUI, interactive interfaces, or 3D visualization as part of an educational intervention or learning environment.
Focused exclusively on technical programming or software development	243	The publication addressed programming, system architecture, or software development without a learning component.
Did not examine learning-tool development, implementation, or evaluation	177	The publication did not investigate the design, application, or assessment of an educational tool.
Not situated within mathematics or computational learning	126	The publication addressed another disciplinary or professional context without a relevant mathematics or computational-learning component.
Non-research publication	74	The publication was an editorial, commentary, opinion paper, or another document without an empirical or review-based research design.
Insufficient methodological or analytical information	56	The publication did not provide adequate information about methods, data, implementation, or findings for systematic analysis.
Total full-text publications excluded	1,092	Total number of publications excluded during the full-text eligibility stage.

The 31 studies retained after full-text assessment constituted the evidence base for descriptive qualitative analysis, thematic coding, inter-study comparison, and narrative synthesis. In contrast, the broader dataset of 1,123 screened records was used for bibliometric and keyword co-occurrence analysis. Figure 1 illustrates the overall review implementation and study-selection process.

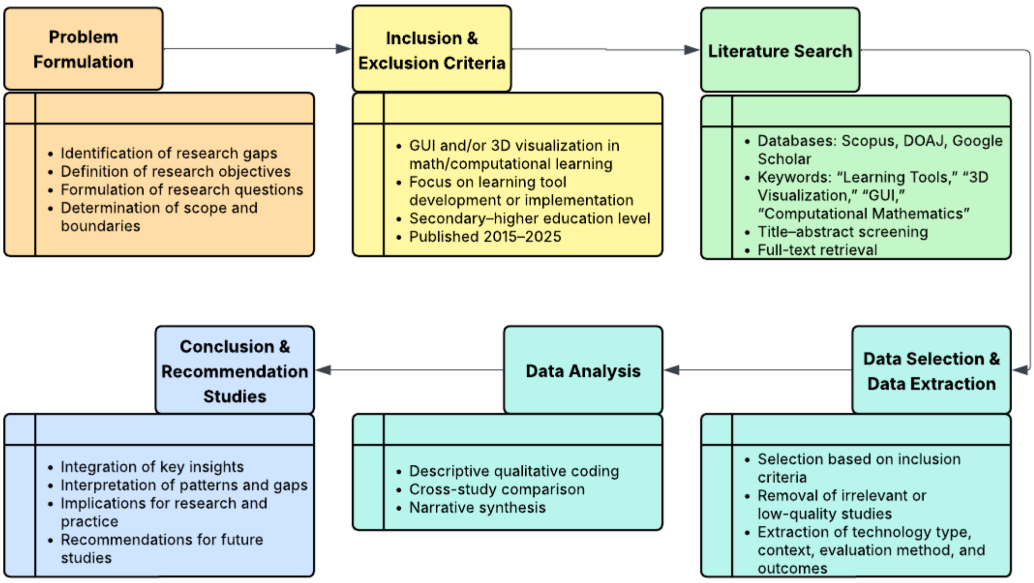

Figure 1. Research Implementation Flow

Data Extraction

Data extraction was conducted collaboratively by the six-member research team using categories aligned with the objectives of the review. Information extracted from each of the 31 included studies comprised the author and publication year, educational level, mathematical or computational topic, research focus, type of GUI or 3D visualization technology, implementation context, research or evaluation method, reported learning outcomes, implementation barriers, and recommendations.

The reported outcomes were organized into cognitive, affective, usability, technical, pedagogical, and institutional categories. Cognitive outcomes included conceptual understanding, mathematical representation, spatial reasoning, and computational-thinking skills. Affective outcomes included motivation, attitudes, engagement, and learning interest. Usability and interaction outcomes included ease of use, interface navigation, and learner interaction with mathematical representations. Technical and contextual information included interface complexity, device compatibility, infrastructure availability, teacher readiness, curriculum alignment, and institutional support.

Methodological Characterization

No formal methodological quality-appraisal or risk-of-bias instrument, such as a Joanna Briggs Institute checklist, was applied in this review. Instead, the methodological characteristics of the 31 included studies were documented descriptively to support cautious cross-study interpretation. These characteristics included research design, educational context, implementation setting, evaluation approach, reported outcomes, and completeness of methodological reporting.

Because the findings were not weighted according to methodological quality, they were interpreted as reported patterns across the included studies rather than as quality-adjusted estimates of effectiveness. The implications of this decision are addressed in the Limitations of the Review subsection.

Data Analysis and Narrative Synthesis

Data analysis was conducted using a descriptive qualitative approach that combined thematic coding, inter-study comparison, and narrative synthesis. Thematic coding was used to identify recurring categories related to technology type, mathematical domain, educational level, research focus, learning outcomes, implementation challenges, and reported recommendations. Inter-study comparison was then used to examine similarities and differences across technological approaches, mathematical topics, educational contexts, research designs, and reported findings.

Narrative synthesis organized the heterogeneous findings into a coherent account of the research landscape. Thematic analysis and narrative synthesis provide complementary strategies for identifying cross-cutting themes while preserving methodological and contextual differences among studies with diverse research designs and outcome measures (Ismail et al., 2023; Gyaurov et al., 2022; Tse et al., 2025). Accordingly, the findings were interpreted as cross-study patterns rather than as pooled causal estimates.

Bibliometric and Keyword Analysis

A complementary bibliometric analysis was conducted using the 1,123 records retained after title and abstract screening. This broader dataset was used to map the thematic structure and keyword relationships within the research field. In contrast, the qualitative, thematic, comparative, and narrative syntheses were based exclusively on the 31 studies that met all full-text eligibility criteria.

Keyword co-occurrence mapping was conducted using VOSviewer version 1.6.17. The unit of analysis consisted of all available author and index keywords in the bibliographic records. The full-counting method was applied so that each occurrence of a keyword received equal weight. A minimum-occurrence threshold of five was used to retain terms that appeared sufficiently frequently across the 1,123 records while reducing fragmentation in the resulting network. VOSviewer's association-strength normalization was used to calculate relationships among terms and generate thematic clusters.

A thesaurus file was used to merge synonymous terms, abbreviations, and spelling variants. For example, "graphical user interface" was merged with "GUI," "three-dimensional visualization" with "3D visualization," "augmented reality" with "AR," "virtual reality" with "VR," and "computational thinking" with "CT." Singular and plural forms, British and American spelling variants, and capitalization differences were also standardized. General terms that did not provide substantive thematic information, including "article," "study," "method," and "result," were excluded before the final network was generated.

The bibliometric analysis identified dominant keywords, relationships among research topics, and the thematic clusters presented in the Results section. Keyword frequency, link strength, and network proximity were interpreted as indicators of research attention and thematic association rather than as evidence of educational effectiveness. Bibliometric mapping therefore complemented, but did not replace, the qualitative synthesis of the 31 included studies.

Analytical Integration

The overall analytical procedure combined descriptive qualitative analysis, thematic coding, inter-study comparison, narrative synthesis, and keyword co-occurrence mapping. The 31 eligible studies provided the primary evidence base for examining the technologies used, reported learning outcomes, implementation contexts, and technical, pedagogical, and institutional challenges. The 1,123 screened records provided the broader dataset for mapping the thematic and intellectual structure of the field.

This distinction ensured that broader bibliometric trends were not conflated with evidence synthesized from the final review corpus. The integrated findings were subsequently used to formulate conclusions and practical recommendations for educators, learning-technology developers, institutions, and future researchers.

RESULTS AND DISCUSSION

Characteristics and Thematic Classification of the Included Studies

Following the selection process described in the Methods section, 31 studies met the eligibility criteria and were included in the qualitative synthesis. The studies were coded according to their principal research focus, technological approach, reported outcomes, and implementation concerns. Because several studies addressed more than one dimension, the categories were not mutually exclusive. Table 4 presents the thematic classification of the included studies and summarizes the principal variables reported within each research focus.

Table 4. Classification of Research Focus and Reported Variables in Studies of GUI and 3D Visualization for Computational Mathematics Learning

No.	Research focus	Representative studies	Reported variables and findings
1	3D visualization in computational mathematics learning	Müller and Zeckzer (2015); Barcelos et al. (2018); Cevikbas et al. (2023); Dewita et al. (2020); Hilyana (2021); Sinaga and Sijabat (2023)	Use of 3D representations to support the interpretation of spatial or complex concepts; strong concentration on geometry-related visualization; and reported contributions to conceptual understanding and mental representation.
2	Graphical User Interfaces in learning	Hilyana (2021); Manihuruk and Sutabri (2024); Maulida and Wahyudin (2025)	Interactive interfaces and multimedia-based representations that support structured access to learning content, conceptual understanding, learning interest, and interaction with mathematical representations.
3	Integration of Computational Thinking	Hickmott et al. (2018); Ye et al. (2023)	Programming, abstraction, decomposition, algorithmic reasoning, and Computational Thinking-oriented instructional strategies in mathematics education.

No.	Research focus	Representative studies	Reported variables and findings
4	AR, VR, and immersive or simulation-based technologies	Schutera et al. (2021); Cevikbas et al. (2023); Wong et al. (2022); Pena et al. (2022)	Immersive, interactive, and simulation-based learning experiences; reported engagement and usability benefits; and implementation concerns related to compatibility, accessibility, and technological requirements.
5	Evidence on learning outcomes from visualization tools	Ramadhanti and Juandi (2022); Rabi et al. (2022); Sinaga and Sijabat (2023); Eyrikh et al. (2022)	Reported effects on geometry and calculus learning, mathematical attitudes, conceptual understanding, and academic performance through visual, interactive, or multisensory tools.
6	Technical challenges in technology implementation	Caroline (2025); Kastawa (2024); Wong et al. (2022); Pena et al. (2022)	Hardware and software limitations, interface complexity, device compatibility, accessibility constraints, and implementation costs.
7	Pedagogical and institutional challenges	Rosyidah (2025); Anggraheni et al. (2025); Patrisius Liber et al. (2024); Muthmainnah et al. (2025)	Curriculum readiness, teacher digital competence, institutional support, student guidance, and professional-development requirements.
8	Need for systematic and interdisciplinary synthesis	Reyes (2021); Bray and Tangney (2017); Barcelos et al. (2018); Müller and Zeckzer (2015)	Fragmentation between technical and pedagogical research, continued use of conventional instructional practices, and the need for collaboration across mathematics education, computer science, and learning-technology research.

Table 4 indicates that the literature covers interconnected technological, cognitive, pedagogical, and institutional dimensions. Studies of 3D visualization and GUI-based learning tools primarily examined the representation and interaction of complex content, whereas studies of Computational Thinking emphasized programming, abstraction, modeling, and algorithmic processes. Research on AR, VR, and simulation-based tools extended this focus toward immersive interaction and experiential learning. Across these categories, the literature also reported recurring technical, pedagogical, and institutional constraints that affected implementation.

The classification further shows that the evidence base was not limited to direct measurements of learning achievement. The included studies also examined motivation, attitudes, usability, user interaction, teacher readiness, infrastructure, and institutional support. These dimensions were retained as distinct analytical categories to avoid treating engagement, usability, and perceived usefulness as equivalent to demonstrated conceptual improvement.

Bibliometric Structure and Keyword Clusters

In addition to the qualitative synthesis of the 31 included studies, bibliometric mapping was conducted using the broader dataset of 1,123 records retained after title and abstract screening. Figure 2 presents the keyword co-occurrence network generated using VOSviewer. Node size represents the relative frequency of a term, links indicate co-occurrence relationships, and colors distinguish groups of closely associated keywords.

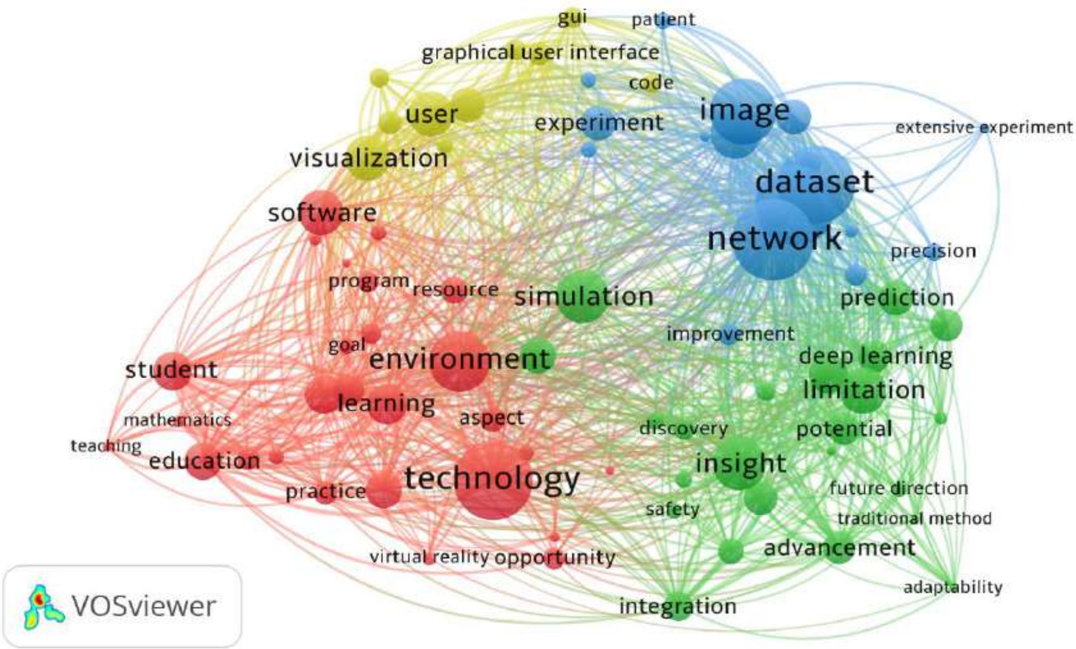

Figure 2. Network Visualization with Keywords: Learning Tools, 3D, Visualization, GUI, Computational Mathematics

As shown in Figure 2, the network contains four major clusters organized around educational technology and learning environments, GUI and visualization, simulation and advanced computational methods, and data- or model-oriented research. Highly connected terms such as “technology,” “environment,” “visualization,” “simulation,” “dataset,” and “network” indicate that the field combines educational, interface-design, computational, and data-analysis perspectives. Table 5 summarizes the dominant keywords and descriptive orientation of each cluster.

The red cluster is organized around the prominent terms “technology,” “environment,” “learning,” “education,” and “student.” Their close connections indicate that the educational use of technology is commonly examined in relation to learning settings, teaching practices, students, and implementation opportunities. The presence of “mathematics” and “virtual reality” within this cluster further connects general educational-technology research with mathematics-related and immersive learning environments.

The yellow cluster is centered on “visualization,” “user,” “GUI,” “graphical user interface,” and “software.” This pattern identifies interface design and visual interaction as a distinct strand of the literature. The connections with “experiment,” “code,” and “program” suggest that GUI and visualization research frequently intersects with software development and empirical evaluation. However, keyword co-occurrence alone does not establish whether these experiments measured usability, cognitive load, learning outcomes, or technical performance; those distinctions were examined through the qualitative synthesis of the 31 eligible studies.

The green and blue clusters represent broader computational and data-oriented dimensions. The green cluster links “simulation,” “insight,” “deep learning,” “prediction,” “integration,” and “discovery,” indicating attention to advanced computational methods and simulation-based inquiry. The blue cluster is dominated by “dataset,” “image,” “network,” and “precision,” reflecting research involving data resources, image-based analysis, network models, and predictive performance. The term “prediction” connects these computational themes across the network, illustrating the relationship between simulation, data processing, and model evaluation.

Table 5. Summary of Keywords and Thematic Orientations Based on VOSviewer Clusters

Cluster	Dominant keywords	Descriptive cluster interpretation	Observed research orientation
Red – Learning, Technology, and Environment	technology, learning, environment, education, student, practice, teaching, mathematics, virtual reality, opportunity	This cluster connects technology with students, teaching practices, mathematics, and learning environments.	Technology-supported education and the conditions under which digital tools are implemented in teaching and learning contexts.
Yellow – Visualization, GUI, and User Interaction	visualization, software, GUI, graphical user interface, user, experiment, code, program	This cluster links visualization and software development with users, interfaces, programming, and experimental work.	Interface design, visual representation, software interaction, and the development or evaluation of GUI-supported systems.
Green – Simulation and Advanced Computational Methods	simulation, insight, deep learning, prediction, improvement, potential, advancement, integration, safety, discovery	This cluster represents simulation, predictive methods, integration, and computationally supported discovery.	Simulation-based analysis, machine-learning-related methods, predictive modeling, and the integration of advanced computational techniques.
Blue – Datasets, Images, and Networks	image, dataset, network, precision, prediction, extensive experiment	This cluster emphasizes data resources, images, networks, prediction, and model-performance terminology.	Data-oriented research, image-based analysis, network models, and evaluation of predictive or computational performance.

Taken together, the four clusters show that GUI and 3D visualization research is situated within a wider interdisciplinary landscape that includes educational technology, software and interface design, simulation, machine learning, image analysis, and predictive modeling. Because the bibliometric analysis was based on 1,123 screened records, the network represents the thematic breadth of the research field rather than the effectiveness of particular educational interventions. Evidence concerning conceptual understanding, motivation, engagement, usability, and implementation was therefore derived from the separate qualitative synthesis of the 31 included studies.

The cluster structure provides the basis for the subsequent presentation of findings concerning the applications of GUI and 3D visualization, reported learning outcomes, implementation challenges, and the temporal development of research from 2015 to 2025.

Discussion

Principal Findings and Research Landscape

The synthesis of the 31 included studies indicates that research on Graphical User Interfaces (GUIs) and 3D visualization in computational mathematics learning remains fragmented across technical, pedagogical, and disciplinary areas. Several studies emphasize the structural or computational characteristics of visualization tools, whereas fewer studies examine how these tools should be integrated with explicit learning objectives, instructional scaffolding, or assessment. Müller and Zeckzer (2015), for example, primarily examine the structure and development of 3D software visualization, while Barcelos et al. (2018) focus on computational representations and Computational Thinking activities with comparatively limited attention to integrated GUI-based pedagogy. Similarly, studies of Computational Thinking in mathematics education often emphasize programming, abstraction, and algorithmic processes more strongly than conceptual mathematical understanding (Hickmott et al., 2018; Ye et al., 2023).

This pattern is consistent with previous systematic evidence showing that mathematics education has adopted digital technologies unevenly and that conventional instructional practices remain influential despite the availability of more transformative tools (Bray & Tangney, 2017). The imbalance between technical development and pedagogical evaluation helps explain why comprehensive frameworks for combining interface design, 3D visualization, mathematical reasoning, and Computational Thinking remain limited. Consequently, the main research gap is not simply the availability of technological tools, but the lack of systematic guidance for integrating those tools into coherent learning designs.

The included studies also show that immersive technologies, particularly augmented reality (AR) and virtual reality (VR), have received increasing attention. Cevikbas et al. (2023) reported that geometry was the most frequently examined mathematical domain across 59 studies, although the reported effectiveness varied among topics, technologies, and learning contexts. The concentration on geometry suggests that GUI and 3D visualization have most often been used to address spatial and representational challenges rather than to support broader areas of computational mathematics. This emphasis is understandable because three-dimensional representations are well suited to geometric objects, transformations, and spatial reasoning; however, it also leaves comparatively fewer applications in calculus, linear algebra, differential equations, numerical methods, and statistics.

Supporting literature from immersive STEM environments reflects a similar pattern. VR-based molecular builders, collaborative AR systems, tangible interfaces, and gesture-controlled environments commonly emphasize spatial interaction, presence, user experience, and engagement (Pietikäinen et al., 2021; Jin et al., 2021; Sereno et al., 2022; Yuan et al., 2022; Yigitbas et al., 2022). Although these studies are not part of the 31-study review corpus, they reinforce the interpretation that immersive interfaces are increasingly designed around direct manipulation and spatial interaction. They also show that usability and engagement are often assessed more frequently than sustained conceptual learning.

Pedagogical Functions of GUI and 3D Visualization

GUI and 3D visualization can support computational mathematics learning by translating abstract, symbolic, or dynamic processes into representations that learners can manipulate and inspect. An effective GUI provides structured access to parameters, commands, visual outputs, and feedback, while 3D visualization enables learners to examine spatial relationships, transformations, and changes from multiple perspectives. Together, these technologies can create an exploratory learning environment in which students test assumptions, modify variables, and observe the corresponding mathematical consequences.

This pedagogical function is supported by literature on dynamic visualization and multiple representations. Dynamic mathematical tools can connect graphs, equations, simulations, and visual objects, thereby helping learners coordinate symbolic, numerical, and visual information (Tiwari et al., 2021; Dahal et al., 2022; Gagani, 2023; Rathour et al., 2024). GeoGebra- and Desmos-type environments similarly demonstrate how dynamic representations can anchor abstract relationships and make transformations more observable (Dahal et al., 2022; Siregar et al., 2024). These benefits arise not merely because the representations are visual, but because learners can move between representations and investigate how a change in one form affects another.

However, interactivity does not automatically result in meaningful learning. The educational value of a GUI or 3D visualization depends on its alignment with instructional goals, the clarity of its visual structure, and the guidance provided during exploration. Instructional scaffolding, guided tasks, explanatory prompts, and immediate feedback help students direct attention toward relevant mathematical relationships rather than merely manipulating visual objects (Kianzad et al., 2021; Castañeda-Miranda et al., 2021; Siregar et al., 2024; Gaviria-Rodríguez et al., 2024). Without such guidance, a visually sophisticated interface may function primarily as an attractive presentation medium rather than as a tool for conceptual development.

User-centered design is therefore essential. Educational interfaces should provide clear navigation, progressive access to complex functions, meaningful feedback, and representations that match the learners' prior knowledge and task requirements (Agrawal, 2024; Castañeda-Miranda et al., 2021; Gaviria-Rodríguez et al., 2024). Interface complexity must also be controlled because excessive visual elements, unfamiliar gestures, or complicated controls can increase extraneous cognitive load and divert attention from the mathematical content (Kianzad et al., 2021; Crandall & Karadoğan, 2021). The appropriate design goal is not maximum visual complexity, but a balanced interface in which each interactive element serves a defined pedagogical function.

Reported Effectiveness and Boundary Conditions

Across the included studies, GUI and 3D visualization were generally associated with reported improvements in conceptual understanding, learning interest, motivation, and interaction with learning materials. Nevertheless, the strength and type of evidence varied considerably among studies. The findings should therefore be interpreted as cross-study patterns rather than as uniform causal effects.

Dewita et al. (2020) reported that 78% of students demonstrated improved understanding after using 3D visualization-based learning media. Hilyana (2021) similarly reported that 83.5% of participants found the interactive multimedia-based learning environment helpful for understanding the target concepts. These findings indicate that interactive and visual representations may make learning content more accessible, although the educational level, disciplinary context, and target concepts differed between the two studies. Manihuruk and Sutabri (2024) further emphasized the role of structured and engaging multimedia design in supporting learning interest, while Maulida and Wahyudin (2025) highlighted the contribution of digital representations to students' construction of mathematical meaning.

Evidence from geometry-oriented tools was comparatively more specific. Ramadhanti and Juandi (2022) reported that 86% of the reviewed studies involving GeoGebra or Cabri 3D showed positive effects on geometrical understanding, with a moderate effect size of 0.674. Sinaga and Sijabat (2023) also found higher geometry-comprehension scores among students who used Cabri 3D than among those in the comparison group. These findings suggest that dynamic and manipulable visual representations are particularly useful when the learning objective involves spatial structures or relationships that are difficult to communicate through static two-dimensional diagrams.

The evidence for calculus and affective outcomes was more varied. Rabi et al. (2022) reported that Microsoft Mathematics supported visualization in calculus learning and was associated with more positive student attitudes. Schutera et al. (2021) similarly found that the cleARmaths application supported an enjoyable and engaging learning experience. Eyrikh et al. (2022) reported an improvement of up to 15% in the academic performance of engineering students using multisensory multimedia. Taken together, these studies indicate that interactive visualization can influence both cognitive and affective dimensions, but they do not demonstrate that every type of GUI or 3D visualization produces equivalent gains across all mathematical domains.

Supporting studies of immersive environments also suggest that motivation, presence, perceived usefulness, and interface satisfaction are often more consistently reported than deep conceptual improvement (Pietikäinen et al., 2021; Cho et al., 2022; Jin et al., 2021; Yigitbas et al., 2022). This distinction is important because engagement and usability may facilitate learning but should not be treated as direct evidence of conceptual mastery. A tool can be enjoyable and easy to use while still requiring stronger instructional integration to produce measurable and transferable understanding.

The effectiveness of GUI and 3D visualization therefore depends on several boundary conditions: the mathematical topic, the quality of the learning task, the interface design, the availability of instructional guidance, and the readiness of teachers and learners. Interactive visualization is most pedagogically valuable when it helps students explain relationships, compare representations, interpret computational processes, and justify conclusions. When these connections are absent, the technology may remain an additional visual layer with limited influence on mathematical reasoning.

Relationship with Computational Thinking

GUI, simulation, and 3D visualization also have the potential to support Computational Thinking by externalizing processes that are otherwise difficult to observe. Through interactive interfaces, students can decompose problems into parameters, explore the effects of algorithmic steps, compare model outputs, and identify patterns in computational results. These activities may support abstraction, decomposition, modeling, and algorithmic reasoning, especially when the interface makes the relationship between input, process, and output explicit.

Supporting studies illustrate how MATLAB GUI-based experiments, GeoGebra applets, and VR-assisted problem-solving environments can be used for modeling and guided exploration (Ridloka et al., 2023; Siregar et al., 2024; Yan, 2024). However, the presence of a computational tool does not automatically develop Computational Thinking. The learning tasks must require students to interpret algorithms, justify parameter choices, evaluate models, and reflect on the computational process. Otherwise, students may interact with the interface procedurally without developing a deeper understanding of the underlying mathematical or computational structure.

Technical, Pedagogical, and Institutional Challenges

The implementation of GUI and 3D visualization in computational mathematics learning is constrained by interconnected technical, pedagogical, and institutional factors. Technical barriers reported across the reviewed studies include low-specification hardware, limited access to educational software, device incompatibility, interface complexity, and implementation costs (Caroline, 2025; Kastawa, 2024; Wong et al., 2022; Pena et al., 2022). Immersive technologies introduce additional concerns, including hardware comfort, fatigue, gesture-recognition reliability, cross-device interoperability, and the need for stable network infrastructure (Jin et al., 2021; Sereno et al., 2022; Lu et al., 2022; Polsinelli et al., 2024).

From a pedagogical perspective, technology integration is limited when teachers lack the digital and instructional competence required to select appropriate tools, design meaningful tasks, and provide effective scaffolding. Rosyidah (2025) identified teacher digital competence as an important condition for technology-supported learning, while Muthmainnah et al. (2025) emphasized the need for continuing professional development. Supporting literature similarly indicates that teachers require both general digital literacy and content-specific pedagogical knowledge to integrate GUI, AR, VR, and 3D visualization effectively (Mystakidis et al., 2021; Oberdörfer et al., 2021; Kossybayeva et al., 2022; Gökbulut & Durnalı, 2023).

Sustained professional development is particularly important because teachers need more than operational knowledge of software. They must learn how to connect representations with curriculum objectives, manage classroom exploration, evaluate student reasoning, and adapt the technology to different learner needs. Long-term training, reflective practice, and collaborative design activities can increase teachers' confidence and improve the pedagogical quality of implementation (Mystakidis et al., 2021; Oberdörfer et al., 2021; Iqbal et al., 2022; Hasumi & Chiu, 2022).

Institutional conditions also shape implementation. Anggraheni et al. (2025) identified policy support and professional development as important components of educational technology adoption. Curriculum alignment, infrastructure investment, technical support, and implementation guidelines are necessary if visualization technology is to move beyond isolated classroom experiments. Supporting literature further emphasizes that sustainable technology integration requires coordination among curriculum development, teacher preparation, infrastructure planning, and institutional policy (Costa et al., 2021; Videla et al., 2021; Leavy et al., 2023; Boltsi et al., 2024).

Equity remains a significant concern. Schools and universities differ in access to compatible devices, licensed software, high-speed internet, and technical assistance. Without deliberate accessibility policies, advanced visualization technologies may widen rather than reduce educational disparities. Open-access, web-based, and device-compatible platforms can reduce some of these barriers, especially when they are supported by low-cost implementation strategies and scalable teacher training (Agrawal, 2024; Iqbal et al., 2022; Leavy et al., 2023; Boltsi et al., 2024).

Temporal Development of Research Themes

The development of research themes from 2015 to 2025 reflects a gradual movement from software structure and basic visual representation toward immersive interfaces, Computational Thinking, user experience, and implementation readiness. Figure 3 summarizes this temporal development.

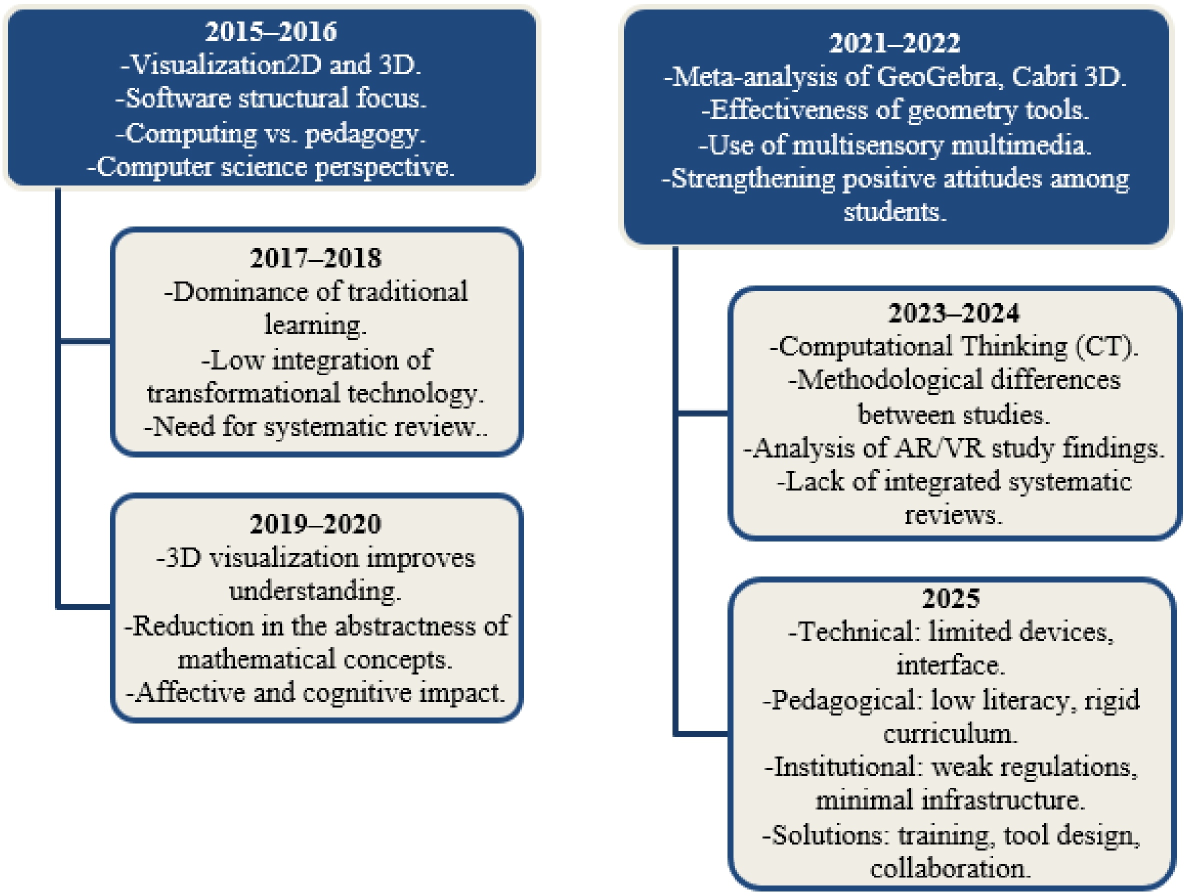

Figure 3. Development of Research Variables

During 2015–2016, research primarily examined 2D and 3D visualization structures, software representation, and the relationship between computing and pedagogy. In 2017–2018, systematic reviews continued to show that traditional instructional practices remained prominent and that transformative uses of technology were still limited. During 2019–2020, greater attention was directed toward 3D visualization as a means of reducing the perceived abstraction of mathematical and scientific concepts and supporting cognitive and affective learning outcomes.

In 2021–2022, the literature increasingly evaluated specific tools and environments, including GeoGebra, Cabri 3D, multisensory multimedia, AR, VR, and tangible interfaces. Research during this period placed greater emphasis on usability, learner attitudes, spatial interaction, and immersive experience. This development is consistent with supporting studies on tangible interfaces, collaborative AR, VR-based learning environments, and three-dimensional user interfaces (Pietikäinen et al., 2021; Jin et al., 2021; Yuan et al., 2022; Sereno et al., 2022; Yigitbas et al., 2022).

During 2023–2024, attention increasingly shifted toward Computational Thinking, mixed-reality interaction, user-centered design, and the integration of advanced computational approaches. Research also became more attentive to interface constraints, cognitive load, presence, collaboration, and cross-platform accessibility. In 2025, the literature placed stronger emphasis on practical implementation barriers, including teacher digital competence, curriculum readiness, institutional policies, infrastructure, and equitable access.

This temporal pattern suggests that the field has matured from asking whether visualization technologies can be developed toward examining how they should be designed, implemented, and sustained. Technological innovation remains important, but the later literature increasingly recognizes that educational effectiveness depends on the readiness of learners, teachers, curricula, institutions, and technological infrastructure.

Limitations of the Review

This review has several limitations. No formal methodological quality appraisal or risk-of-bias assessment was applied, and the included studies varied in research design, educational context, technology, and outcome measurement. The search was also limited to open-access publications written in English or Indonesian and indexed in Scopus, DOAJ, or Google Scholar between 2015 and 2025. In addition, the bibliometric analysis used 1,123 screened records, whereas the qualitative synthesis was based on 31 eligible studies; therefore, the identified clusters describe the broader structure of the field rather than direct evidence of effectiveness.

Nevertheless, the transparent selection process, clear separation of analytical datasets, theory-informed interpretation, and cross-study comparison provide a credible basis for describing current research conditions, identifying major trends and gaps, and clarifying the role of GUI and 3D visualization in computational mathematics education. The findings should therefore be interpreted as theoretically grounded descriptive patterns rather than pooled causal estimates.

Implications for Practice and Future Research

The findings suggest that educators should select GUI and 3D visualization tools according to explicit learning objectives rather than technological novelty. Learning activities should require students to manipulate representations, compare outputs, explain observed patterns, and connect visual evidence with symbolic or numerical reasoning. Developers should prioritize usability, accessibility, progressive interface complexity, and meaningful feedback. Institutions should support implementation through sustained professional development, compatible infrastructure, curriculum alignment, and equitable access policies.

Future studies should extend the application of GUI and 3D visualization beyond geometry to areas such as calculus, linear algebra, differential equations, numerical methods, statistics, and data modeling. Research should also distinguish more clearly among conceptual understanding, learning achievement, engagement, motivation, usability, presence, and cognitive load. Standardized measures would improve comparability across studies, while longitudinal and experimental designs would provide stronger evidence regarding retention, transfer, and sustained implementation.

Integrated pedagogical frameworks are also needed to connect interface design, multiple representations, instructional scaffolding, Computational Thinking, and mathematical reasoning. Frameworks for immersive and technology-supported learning suggest that educational effects emerge from the interaction among technological affordances, learner characteristics, instructional design, and contextual conditions rather than from immersion alone (Makransky & Petersen, 2021; Mystakidis et al., 2021; Videla et al., 2021; Leavy et al., 2023).

Finally, cross-national and interdisciplinary research could clarify how teacher readiness, infrastructure, culture, curriculum, and institutional policy influence implementation. Collaboration among mathematics educators, computer scientists, interface designers, and cognitive-science researchers is needed to ensure that future GUI and 3D visualization systems are not only technically advanced but also pedagogically meaningful, accessible, and empirically validated.

CONCLUSIONS

This systematic review of 31 studies indicates that Graphical User Interfaces (GUIs) and 3D visualization can support computational mathematics learning by making abstract concepts more accessible, enabling interaction with complex mathematical representations, and promoting student engagement. The reviewed evidence suggests that these technologies are most beneficial when they are aligned with explicit learning objectives, supported by instructional scaffolding, and embedded within pedagogically grounded learning activities. Their effectiveness therefore depends not only on technological functionality but also on the quality of interface design, instructional guidance, and classroom implementation.

The findings also reveal several limitations in the current research landscape. Existing studies remain fragmented across technological, mathematical, and educational contexts, with a strong concentration on geometry and spatial representation. Evidence from non-geometry domains, including calculus, linear algebra, differential equations, numerical methods, and statistics, remains comparatively limited. In addition, differences in research designs, evaluation instruments, educational levels, and reported outcomes restrict direct comparison across studies.

From a practical perspective, the development of GUI- and 3D-based learning tools should prioritize usability, accessibility, representational clarity, and meaningful interaction with mathematical content. Educators should integrate these tools with guided exploration, explanatory feedback, and tasks that connect visual, symbolic, numerical, and computational representations. At the institutional level, sustainable implementation requires curriculum alignment, continuing teacher professional development, adequate infrastructure, technical support, and policies that promote equitable access to digital learning resources.

Overall, GUI and 3D visualization should not be treated as isolated technical additions to conventional instruction. Their educational contribution depends on how effectively technological affordances are integrated with mathematical reasoning, Computational Thinking, and appropriate pedagogical strategies. Advancing this field will require closer collaboration among mathematics educators, computer scientists, interface designers, and cognitive-science researchers.

RECOMMENDATIONS

Future research should develop and empirically evaluate integrated learning environments that combine user-friendly GUIs, interactive simulations, and immersive 3D visualization. These environments should be designed to support mathematical understanding and Computational Thinking processes, including abstraction, decomposition, modeling, algorithmic reasoning, and interpretation of computational results. Research should also examine how augmented reality, virtual reality, and artificial intelligence can provide adaptive scaffolding, personalized feedback, and differentiated levels of task complexity.

Further studies should extend beyond geometry-related topics and investigate applications in calculus, linear algebra, differential equations, numerical methods, statistics, and data modeling. Longitudinal, experimental, quasi-experimental, and cross-national designs are needed to evaluate conceptual retention, transfer of learning, sustained engagement, and implementation across different educational levels and learner characteristics. Researchers should also distinguish clearly among conceptual understanding, academic achievement, motivation, engagement, usability, presence, and cognitive load.

More consistent evaluation procedures are required to improve comparability across studies. Future investigations should use validated instruments and clearly report participant characteristics, intervention duration, technological specifications, instructional procedures, and implementation conditions. The development and empirical validation of standardized pedagogical frameworks would also help connect interface design, multiple representations, instructional scaffolding, Computational Thinking, and mathematical reasoning.

For educators and developers, learning tools should provide intuitive navigation, progressive interface complexity, meaningful feedback, and clear connections among visual, symbolic, numerical, and computational representations. For institutions and policymakers, implementation should be supported through sustained professional development, curriculum integration, affordable and device-compatible infrastructure, and equitable-access policies. Open-access and web-based platforms should be prioritized where appropriate to reduce technological disparities and support wider adoption.

These recommendations should be implemented with attention to infrastructure limitations, development costs, teacher readiness, rapid technological change, and differences among educational contexts. Addressing these conditions is essential to ensure that GUI and 3D visualization contribute meaningfully and sustainably to computational mathematics education.

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Ethical Approval
This study does not involve human or animal subjects. Therefore, ethical approval is not required.

Data Availability
All data used in this research are derived from previously published articles included in the systematic literature review.

Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Syaharuddin	✓	✓	✓	✓	✓	✓		✓	✓	✓				
Abdillah	✓	✓				✓			✓	✓				
Saba Mehmood	✓		✓	✓	✓		✓			✓	✓			
Wasim Raza	✓			✓	✓	✓				✓	✓			
Alfiana Sahraini	✓	✓						✓	✓	✓		✓	✓	
S Emmanuel Fadugba	✓									✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

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