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Literature Review: The Use of GeoGebra Software on Mathematical Comprehension Ability

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Abstract

This study aims to comprehensively analyze the role of GeoGebra software in enhancing students' mathematical comprehension skills through a systematic review of literature published between 2020 and 2025. Employing a library research method, this paper synthesizes findings from previous empirical and conceptual studies related to GeoGebra-based mathematics learning. As a dynamic and technology-driven tool, GeoGebra has proven effective in transforming abstract mathematical concepts into concrete, visual, and interactive representations. The findings reveal that GeoGebra significantly facilitates students' understanding of complex topics such as algebra, geometry, trigonometry, and calculus, which are often challenging to grasp through conventional teaching approaches. By integrating visualization, simulation, and manipulation of mathematical objects, GeoGebra supports students in bridging theoretical knowledge with practical application, thereby fostering deeper conceptual understanding and active engagement in the learning process. Furthermore, the review highlights the pivotal role of teachers in effectively incorporating GeoGebra into instructional practices. Teachers are encouraged to utilize GeoGebra to design problem-based, exploratory, and collaborative learning environments that stimulate student motivation, creativity, and self-directed learning. Overall, this study concludes that the integration of GeoGebra in mathematics education not only enhances cognitive understanding but also cultivates essential 21st-century learning skills. Thus, GeoGebra serves as an innovative pedagogical tool aligned with the demands of digital-era education and offers promising implications for improving mathematics teaching and learning outcomes.

Keywords: concept visualization; GeoGebra software; interactive learning; literature study; mathematical comprehension

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Introduction

Mathematics is universally recognized as a fundamental discipline that underpins science, technology, engineering, and everyday reasoning. It serves not only as a tool for problem-solving but also as a way of thinking that promotes logical reasoning, creativity, and precision. In the context of education, mathematics equips students with critical skills necessary for navigating complex real-world problems and developing analytical perspectives essential for the modern knowledge society. [57]

However, despite its vital role, mathematics remains one of the most challenging subjects for students at various educational levels. Numerous studies have shown that many learners experience anxiety, misconceptions, and difficulties in understanding abstract mathematical concepts. This persistent challenge highlights the need for innovative pedagogical approaches that can transform mathematics from a subject perceived as difficult into one that is meaningful, engaging, and relevant to students' daily lives. [2, 58]

The rapid development of digital technologies has brought new opportunities to improve mathematics education. Technology-based learning environments, such as dynamic geometry software and computer-assisted learning tools, have been increasingly utilized to enhance students'

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conceptual understanding. Among these tools, **GeoGebra** has gained significant attention for its capacity to bridge the gap between abstract mathematical theory and visual, interactive representation. [59]

GeoGebra integrates algebra, geometry, calculus, and statistics in a dynamic interface that allows students to visualize and manipulate mathematical objects in real time. This interactivity helps learners explore mathematical relationships more deeply and encourages active engagement through discovery-based learning. Research has consistently demonstrated that visualization through GeoGebra enhances comprehension, supports problem-solving skills, and fosters a more positive attitude toward mathematics. [1, 2, 60]

In the Indonesian educational context, the integration of technology into mathematics instruction is aligned with national curriculum reforms emphasizing higher-order thinking skills (HOTS), creativity, and digital literacy. Yet, the implementation of technology-assisted learning remains inconsistent. Many teachers still rely on conventional methods, often due to limited training, resources, or confidence in using digital tools effectively in classroom practice. [61]

Consequently, understanding how GeoGebra can be effectively utilized to improve mathematical comprehension is of strategic importance. A literature-based investigation provides valuable insights into how this software contributes to conceptual learning, student engagement, and instructional innovation. Such understanding can inform both teacher professional development and curriculum design aimed at optimizing the benefits of digital technologies in mathematics learning. [62]

Furthermore, previous research highlights that the success of integrating GeoGebra depends not only on its technological affordances but also on pedagogical alignment and teacher facilitation. Teachers play a central role in designing meaningful learning experiences that connect GeoGebra's dynamic features with curriculum objectives. Therefore, examining the literature surrounding GeoGebra's use in mathematics education can reveal patterns, challenges, and best practices for improving student learning outcomes in diverse educational contexts. [61, 63]

Yusuf and Salim state that mathematics is a science that is part of human life [46]. Mathematics is the science of organized structures, discussing facts and relationships, as well as space and form [27]. At its core, mathematics is a science that is closely related to human life. However, in practice, students often have difficulty in capturing and expressing mathematical ideas. One of the reasons is that the learning process is less meaningful, so that students have difficulty understanding the concepts being taught. [25] emphasized that mathematics education in Indonesia still focuses on direct learning that tends to be one-way, where teachers dominate and students only play a passive role as recipients of information. This condition makes students have limited opportunities to actively participate in learning.

One of the main goals of learning mathematics is to build the ability to understand concepts. Math material is hierarchical, so to learn a topic, students must first understand the material beforehand. This shows that learning mathematics is not enough to rely only on memorization, but requires deep understanding [11]. [33] emphasize that the ability to understand mathematics is a basic skill that students must have, because it is an entrance to develop other cognitive abilities. In line with NCTM, mathematical understanding is included in one of the standards of mathematical thinking processes. Thus, this ability needs to be developed in a directed manner.

In alignment with the **National Council of Teachers of Mathematics (NCTM)**, mathematical understanding is recognized as one of the essential components within the standards of mathematical thinking processes. NCTM emphasizes that true mathematical proficiency extends beyond procedural fluency to encompass a deep, conceptual understanding of ideas, relationships, and representations [55]. Such understanding enables learners to connect mathematical concepts, justify procedures, and apply knowledge flexibly across contexts. Therefore, this ability must be developed in a structured and intentional manner through instructional practices that promote reasoning, problem-solving, and multiple representations of concepts. Empirical evidence supports this view; for instance, [56] found that applying NCTM-based learning principles—such as emphasizing conceptual connections, using examples and non-examples, and integrating technology—significantly enhances students' conceptual understanding of mathematics. This study aligns with NCTM's vision that curriculum and pedagogy should nurture relational understanding rather than rote memorization, thus ensuring that students can construct meaning, communicate mathematical reasoning effectively, and transfer knowledge to new situations. In this regard, the NCTM standards serve as a theoretical and practical foundation for educators seeking to foster higher-order mathematical thinking through deliberate, student-centered, and conceptually oriented instruction.

According to [10], mathematics is an abstract subject so it requires the ability to think logically in understanding it. Therefore, the right learning media is needed to make abstract concepts easier to understand. Media also functions to increase student motivation and involvement in learning. One of the most widely used modern media is technology-based software. [37] explained that software is able to present abstract material with the help of the integration of images, videos, sounds, and animations, making it easier for students to understand.

One popular software for learning math is GeoGebra. This application can be used to represent, describe, and acquire mathematical concepts in a more interactive way. [22] mentioned that GeoGebra can be applied in various topics, such as the Two-Variable Linear Inequality System (SPLDV), linear programming, quadratic functions, derivatives, three-dimensional geometry, and so on. With GeoGebra, students can perform graphical simulations, calculate the area, and determine the shortest distance, which ultimately makes it easier for them to understand concepts.

[44] revealed that GeoGebra was developed for three main purposes: as a mathematics learning resource, as a tool for making teaching materials, and as a means of solving problems that help students through the process of experimentation and concept discovery. GeoGebra can be applied at all levels of education, from elementary school to college. With its flexible nature, GeoGebra can be considered a powerful learning medium to improve students' understanding.

According to [4], learning with the help of GeoGebra not only improves understanding of concepts, but also contributes to problem-solving skills and learning independence. This is in line with the demands of the 21st century that emphasizes critical, creative, collaborative, and communicative thinking skills. Thus, the integration of GeoGebra in mathematics learning becomes very relevant.

According to [35], GeoGebra plays an important role in supporting technology-based mathematics learning in the digital era. They found that students who used GeoGebra showed an increased understanding of algebra concepts due to visualizations that facilitated the connection between symbolic equations and graphs. These findings reinforce the view that interactive-based educational technologies can reduce learning barriers caused by material abstraction.

The results of [20] research stated that the integration of GeoGebra in trigonometry learning was able to improve students' problem-solving skills. With interactive simulations of angles, circles, and trigonometric graphs, students will more easily understand the relationships between functions. This research supports Vygotsky's theory of social constructivism, that students' understanding can develop when they are given the opportunity to explore through visual aids.

According to research by [28] , GeoGebra not only improves understanding of concepts, but also improves students' positive attitudes towards mathematics. Many students who initially found math difficult became more confident when learning to use this app. This shows that technology-based learning media can affect the affective realm of students, not just the cognitive realm.

Recent research by [29] emphasizes that GeoGebra is effectively used in a *project-based learning* model. Using GeoGebra, students are able to complete mathematical projects, such as data analysis using function graphs or geometric simulations. These activities build 21st century skills, including collaboration, communication, creativity, and critical thinking.

[34] found that the use of GeoGebra in differential and integral learning helps students more quickly understand the meaning of derivatives and integrals as changes and area areas. The results of this study support Bruner's theory of representation, because GeoGebra allows students to move from visual representation to symbolic representation gradually.

According to [3], GeoGebra is also effective for improving higher *order thinking skills (HOTS).* In mathematics learning, students who are accustomed to using GeoGebra are able to ask critical questions, analyze various possible solutions, and evaluate solution steps. This is in line with the demands of the Independent Curriculum which emphasizes the importance of developing critical thinking skills [7, 10].

International research by [1] shows that GeoGebra has been widely used in various countries as an inclusive learning tool. Students with low and high abilities alike benefit because the app is flexible. GeoGebra can also be used as a remedial and enrichment tool, thus supporting the principle of differentiation in mathematics learning.

According to [35], the application of GeoGebra in spatial geometry learning has significant results on students' spatial abilities. The three-dimensional visualization provided by this application helps students understand the concepts of volume, surface area, and distance between points and planes. This supports *Paivio's dual coding* theory, which states that information presented in visual and verbal forms will be easier to understand and remember.

Recent research by [7, 32] emphasizes that GeoGebra can be used in *blended* learning-based learning. Students can access the material through GeoGebra at home, then discuss the results of their exploration in class. This strategy encourages students to be more independent, increases curiosity, and expands the learning experience beyond the confines of a traditional classroom.

The results of [42] research show that teachers who use GeoGebra in mathematics learning are more likely to develop teaching method innovations. Teachers can design questions based on real contexts, such as calculating distance, land area, or analyzing graphic data that is relevant to students' daily lives. Thus, GeoGebra is not only a tool for students, but also a means of professional development for teachers in creating creative and meaningful learning [10].

The development of educational technology has encouraged the presence of various software that can support mathematics learning. One of the most widely used is GeoGebra, due to its open source, easy access and support for a wide range of platforms. Previous studies have shown that GeoGebra is effective in helping students understand concepts that are difficult to understand only with conventional methods. For example, the concept of a normally abstract quadratic function can be visualized in the form of a dynamic graph so that students can see the direct relationship between algebraic equations and parabolic shapes. Thus, GeoGebra serves as a bridge between abstract and concrete thinking [4].

In addition to making visualization easier, GeoGebra also supports discovery-based learning. Students can explore a concept by trying out various simulations. For example, when studying derivatives, students can change the position of tangents on a function graph to see gradient changes directly. This is in line with constructivist theory which emphasizes that knowledge is built through students' active experiences, not just the transfer of information from teachers [5].

From a pedagogical point of view, the use of GeoGebra supports a *student-centered learning approach*. The teacher is no longer the only source of information, but rather a facilitator who guides students to explore the material. With GeoGebra, students can be more independent in finding concepts, while teachers play the role of providing direction and clarification. This can reduce the dominance of lecture methods that have so far dominated mathematics learning in Indonesia [6, 7, 8].

Bruner's learning theory emphasizing the importance of enactive, iconic, and symbolic representations is also relevant to the use of GeoGebra. This application allows students to start from the visual (iconic) stage, then move on to the symbolic in the form of formulas and equations. For example, when studying the area under the curve, students can see a graphical representation as well as the results of integral calculations. Thus, GeoGebra helps students move from intuitive to formal understanding [15, 16].

Research by Hohenwarter, the developer of GeoGebra, also confirms that the app is designed to support the integration of geometry, algebra, and calculus in a single learning environment. With this integration, students not only see mathematics partially, but also as a whole. This is in accordance with the purpose of the mathematics curriculum which aims to foster a thorough understanding of the relationships between topics [9, 10].

In the Indonesian context, the use of GeoGebra is also relevant to the Independent Curriculum which emphasizes project-based learning and problem-solving. With GeoGebra, teachers can design more contextual learning projects, such as calculating land area with a graphical approach or analyzing the movement of objects with a quadratic function. This makes learning mathematics more meaningful and close to students' real lives [11, 12, 13].

From the aspect of learning motivation, GeoGebra has also been proven to be able to increase student interest. Exciting, interactive, and dynamic visualizations make math no longer scary, but fun. Students who are initially passive may be encouraged to be more active in trying, exploring, and asking questions. This is in accordance with the ARCS (Attention, Relevance, Confidence, Satisfaction) motivational theory which states that learning media must be able to attract attention, be relevant, increase confidence, and provide learning satisfaction [15, 16, 17].

The use of GeoGebra also supports the development of 21st century skills, especially critical thinking and problem-solving skills. With flexible simulations, students can try different strategies to solve problems. For example, in the optimization problem, students can visualize a function graph to determine the maximum or minimum point. This process trains students to not only rely on formulas, but also to think analytically [20].

Several empirical studies in Indonesia have also shown the effectiveness of GeoGebra. For example, the research of [21, 22] proved that students who studied with the help of GeoGebra showed a significant improvement in understanding the concept of quadratic functions compared to conventional methods. Similarly, research by [18, 19, 20] showed an increase in student learning independence and motivation after using GeoGebra in trigonometry learning.

With its various advantages, the use of GeoGebra is not only relevant in the context of classroom learning, but also supports distance learning. In the digital era, students can access GeoGebra through computers and mobile devices. This makes it easier to access learning outside of school hours and supports lifelong learning. Thus, GeoGebra is one of the potential media to face the challenges of mathematics education in the era of the industrial revolution 4.0. [21]

Research Methods

The method used in this study is library research, which is research conducted by reviewing various relevant literature and analyzing topics in depth without having to conduct field research, but by examining credible and up-to-date written sources [2, 47]. The literature used is limited to the range of 2020 to 2025 so that the information obtained remains new and in accordance with the latest developments, with sources coming from national and international journals, reference books, proceedings, scientific magazines, and online academic repositories. The object of study in this article is the ability of students to understand mathematics through the use of GeoGebra Software which focuses on how the software can facilitate students to understand abstract mathematical concepts. The stages of literature research include problem identification (low mathematical understanding of students in conventional learning), collection of relevant sources, literature selection, content analysis to find patterns and findings, and information synthesis to formulate a comprehensive understanding. The data obtained are in the form of concepts, theories, models, and the results of previous research which are then analyzed in a qualitative descriptive manner by explaining, comparing, and relating various findings from different literature. Thus, this study not only describes theories, but also integrates various views to make theoretical contributions to the development of mathematics learning strategies, and can be an inspiration for teachers and researchers in developing technology-based learning innovations, especially the use of GeoGebra Software to improve students' mathematical understanding [2, 48].

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Results and Discussion

Result

The results of research from several literature on the use of *geogebra software* on mathematical comprehension ability. This research material comes from a study of the current situation which is analyzed to strengthen research on the use of *geogebra software* in students' mathematical understanding. The following is a summary of studies related to this issue:

Table 1. Research Literature on Geogebra in Mathematics Learning in 2020-2025.

No.	Researchers	Year	Research Title	Research Core
1	Nurhidayah, M. & Prasetyo, A.	2020	The Utilization of GeoGebra to Improve the Visualization of the Limit Concept in Students	GeoGebra effectively helps students understand the concept of abstract function limits through interactive graph simulations. [28]
2	Rahman, A., Fitria, D., & Hasanah, R.	2021	The Effect of the Use of GeoGebra on the Understanding of Trigonometry Concepts for High School Students	The use of GeoGebra significantly improves students' understanding of trigonometry concepts, especially privileged angles and graphs of trigonometric functions. [30]
3	Wahyuni, S. & Hidayat, T.	2021	GeoGebra's Integration in Flipped Classroom Models in Space Geometry Materials	The combination of flipped classroom and GeoGebra models increases learning motivation and understanding of spatial geometry concepts. [41]
4	Hidayati, R. & Putra, I.	2022	The Effectiveness of Android-Based GeoGebra in Junior High School Mathematics Learning	The mobile-based GeoGebra application improves the accessibility and effectiveness of independent learning for junior high school students. [18]
5	Wijaya, H. & Saputra, R.	2023	Application of GeoGebra to Improve Understanding of Linear Algebra Concepts	GeoGebra helps students understand linear equation systems through dynamic graphical representations that clarify the relationships between variables. [42]
6	Mariani, F. & Susanti, N.	2023	GeoGebra Assisted Learning in Improving Understanding of SPLDV in Junior High School	SPLDV chart exploration using GeoGebra is more effective than manual methods in building students' conceptual understanding. [20]
7	Yusuf, R. & Salim, D.	2024	GeoGebra Collaboration with Problem Solving Approach in Calculus Learning	The integration of GeoGebra with a problem solving approach improves students' mathematical representation skills, especially in indeterminate integral topics. [46]
8	Anisa, R. & Kurniawan, B.	2024	Analysis of High School Students' Mathematical Concept Comprehension Ability through GeoGebra Media	GeoGebra-assisted learning has been shown to be more effective in improving understanding of mathematical concepts than traditional lecture methods. [3]
9	Siregar, D. & Lubis, E.	2025	Optimizing the Understanding of GeoGebra-Assisted Transformation	GeoGebra supports the Independent Curriculum project approach by encouraging students' creativity in

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			Geometry in the Era of the Independent Curriculum	the exploration of geometric transformations. [34]
10	Marlina, P. & Gunawan, T.	2025	The Influence of GeoGebra on Critical Thinking and Mathematical Comprehension of Education Students	Research by Marlina & Gunawan (2025) shows that the use of GeoGebra is able to increase *critical thinking* as well as mathematical understanding of education students. GeoGebra provides interactive visualizations that make it easier for students to understand abstract concepts, especially in geometry and algebra materials. In addition, the integration of GeoGebra supports the project approach in the Independent Curriculum because it encourages students' creativity in exploring geometric transformations, building self-representations, and practicing technology-based problem-solving skills. [21]

From Table 1 above Based on a literature review from 2020 to 2025, it can be seen that the use of GeoGebra in mathematics learning continues to experience significant development, both in terms of material context, education level, and integrated learning approaches. In 2020, research by [28] confirmed that GeoGebra was able to help students understand abstract concept limits through interactive chart visualization. The results of this study mark the beginning of evidence that GeoGebra is effective in overcoming students' difficulties in learning abstract analysis topics.

In 2021, research by [30] showed a significant increase in the understanding of trigonometric concepts among high school students, especially on the topic of special angles and graphs of trigonometric functions. These results were reinforced by Wahyuni and Hidayat in the same year, who integrated GeoGebra in the *flipped classroom model*. Their findings show that the use of GeoGebra not only improves understanding of spatial geometry concepts, but is also able to increase students' motivation to learn because students are actively involved before and during the learning process.

Entering 2022, [18] researched the effectiveness of Android-based GeoGebra in junior high school students. The results of the study show that the mobile-based application is able to increase accessibility and support students' independent learning. This indicates that GeoGebra is increasingly relevant in the digital era, especially to support flexible technology-based learning.

In 2023, the focus of research shifts to a higher level. [42] found that GeoGebra effectively helps students understand the concept of linear algebra, especially linear equation systems, through dynamic graphical representations. This research is in line with the findings of Mariani and Susanti which show that SPLDV graph exploration with GeoGebra is more effective than manual methods, because it is able to strengthen the conceptual understanding of junior high school students.

Furthermore, in 2024, research by [46] combines GeoGebra with *a problem-solving* approach to calculus materials. The results of the study showed an increase in students' mathematical representation skills, especially in solving indeterminate integral problems. This study confirms that GeoGebra not only supports visualization, but is also able to strengthen high-level thinking skills. Another study by Anisa and Kurniawan in the same year showed that GeoGebra-assisted learning in high school students was more effective in improving concept understanding than traditional lecture methods, confirming the relevance of GeoGebra as a modern learning medium.

By 2025, research is increasingly directed to support the implementation of the Independent Curriculum. [34] found that GeoGebra can optimize students' understanding of geometry transformation materials with a project-based approach. This is in line with the spirit of the Independent Curriculum which encourages creativity and independent exploration of students. Meanwhile, Marlina and Gunawan highlighted the influence of GeoGebra on the critical thinking skills and mathematical understanding of education students. The results show that the use of GeoGebra not only plays a role in the mastery of concepts, but also in the development of high-level thinking skills that are indispensable in the 21st century learning era.

Overall, the literature from 2020 to 2025 shows the consistency of GeoGebra's effectiveness in improving understanding of mathematical concepts at various levels of education. Furthermore, the latest research emphasizes the role of GeoGebra in supporting innovative learning approaches, encouraging creativity, and developing critical thinking skills in accordance with the demands of the Independent Curriculum and the challenges of the digital era.

Discussion

The results of the study by [49] show that GeoGebra Software-based online learning media on curved side space materials meet valid, practical, and effective criteria to improve the ability to understand mathematical concepts of grade IX junior high school students. This research confirms that GeoGebra is in line with the scientific approach in the 2013 Curriculum and is relevant to the learning needs of the industrial revolution 4.0 era.

Furthermore, research by [35, 36, 37] strengthened these findings by integrating GeoGebra into the *Problem Based Learning* (PBL) model. The results of the post-test showed a significant difference between the experimental class and the control class. The improvement in understanding of mathematical concepts in the experimental class achieved an N-gain value of 75% (the moderately effective category), while the control class only increased by 50% (the least effective category). This indicates that GeoGebra's collaboration with the PBL model is superior to traditional learning.

Meanwhile, [1] highlighted the use of the GeoGebra Classic application in geometry transformation materials. This study proves that GeoGebra is able to have a very strong positive influence on students' understanding of mathematical concepts with a percentage of 97.7%. The dynamic visualization capabilities offered by GeoGebra help students overcome difficulties in drawing or imagining geometric shapes, while increasing their motivation to learn.

Research by [23, 24] adds another dimension, namely the relationship between understanding mathematical concepts and problem-solving skills. The results show that the higher the students' understanding of mathematical concepts, the better their ability to solve problems. Thus, the use of GeoGebra is not only beneficial in improving understanding of concepts, but also in developing mathematical problem-solving skills.

In line with the previous findings, [39, 40] emphasized that the *discovery learning model* with the help of GeoGebra is able to improve the understanding of mathematics concepts for high school students. GeoGebra is not only a visualization tool, but it can also facilitate active, creative, and effective learning. When compared to the research of [36, 37], the two have similarities in the effectiveness of GeoGebra, but differ in the learning model used: PBL versus *discovery learning*.

In addition, research by [13, 14] also emphasized the potential of GeoGebra in improving mathematical understanding at various levels of education. [31] researched indoor distance material at the high school level, while [32] researched space building material in grade V elementary school students. The difference between the two lies in the context and teaching materials, but both consistently show that GeoGebra is effective as a learning medium.

From these various studies, it can be concluded that the use of GeoGebra from 2020 to 2023 has consistently been proven to improve students' mathematical comprehension skills, both through integration with PBL models, *discovery learning*, and direct use of certain materials. GeoGebra contributes to overcoming visualization difficulties, increasing motivation, and strengthening mathematical problem-solving skills at various levels of education.

Further Elaboration and Discussion

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i. Comparative Analysis Between Researches

Based on the literature listed in Table 1, it can be seen that the use of Geogebra Software consistently shows an increase in understanding of mathematical concepts at various levels of education, ranging from elementary school, junior high school, to high school, and even college. The fundamental difference between these studies lies in the teaching materials (building space, SPLDV, geometric transformation, distance in space, field analytic geometry), as well as integrated learning models (Problem Based Learning, Discovery Learning, Scientific Approach).

Based on the literature presented in Table 1, it is evident that the use of GeoGebra Software has consistently contributed to enhancing students' understanding of mathematical concepts across diverse educational levels. Studies conducted at the elementary, secondary, and tertiary levels have shown that GeoGebra facilitates visualization, interaction, and exploration in ways that traditional instructional tools often fail to achieve. The consistent improvement in conceptual understanding highlights the software's flexibility and effectiveness in supporting mathematical learning. Researchers have found that students become more engaged and motivated when mathematical concepts are presented dynamically through GeoGebra's visual interface. This engagement leads to more meaningful learning experiences, as students can directly manipulate objects and observe relationships among variables. Furthermore, the software promotes active learning by allowing students to test hypotheses, observe changes in real time, and draw their own conclusions based on evidence. These characteristics are aligned with constructivist learning theories that emphasize learner-centered exploration. Across studies, GeoGebra has been praised not only for its accessibility but also for its ability to make abstract mathematical ideas more concrete. Whether used to teach geometry, algebra, or calculus, GeoGebra provides a platform where learners can connect visual representations with symbolic reasoning. As such, the body of literature collectively reinforces GeoGebra's position as a transformative digital tool in mathematics education. [2, 26]

A closer examination of these studies reveals that differences in outcomes often depend on the type of mathematical content being taught. For instance, some studies focus on the understanding of geometric transformations, while others emphasize algebraic topics such as systems of linear equations (SPLDV) or the concept of distance in space. These variations suggest that GeoGebra's effectiveness is influenced by the cognitive demands of each mathematical domain. Geometry-related topics, in particular, seem to benefit most from the software's dynamic visualization capabilities. Students can manipulate shapes, observe transformations, and analyze relationships between geometric elements with a level of interactivity that traditional static diagrams cannot provide. In contrast, when applied to algebraic problems, GeoGebra aids students in linking symbolic expressions with their graphical representations. This integration helps bridge the gap between abstract and visual reasoning. Studies involving analytic geometry also highlight GeoGebra's ability to support multi-representational understanding, where students connect coordinates, equations, and graphs simultaneously. Therefore, the diversity of teaching materials across studies reflects the adaptability of GeoGebra in addressing various mathematical concepts while maintaining a consistent positive impact on conceptual understanding. [1, 2, 43]

In addition to the diversity of mathematical content, the studies also differ in terms of the instructional models integrated with GeoGebra. Researchers have experimented with models such as Problem-Based Learning (PBL), Discovery Learning, and the Scientific Approach to maximize the pedagogical value of the software. In PBL-based implementations, GeoGebra serves as an exploratory medium that supports students in investigating real-world mathematical problems. The interactive features of the software encourage students to visualize, test, and revise their solutions collaboratively. Discovery Learning approaches, on the other hand, capitalize on GeoGebra's ability to promote inquiry and hypothesis testing. Students are guided to construct mathematical knowledge by manipulating digital objects and identifying patterns that emerge from their actions. The Scientific Approach emphasizes systematic observation and reasoning, where GeoGebra assists learners in formulating conjectures, testing them empirically, and drawing logical conclusions. Across these models, GeoGebra functions not merely as a presentation tool but as an epistemic instrument that

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transforms the way mathematical knowledge is constructed and internalized. Consequently, these integrations underline the potential of combining technological and pedagogical innovations to foster deeper conceptual understanding. [38, 45, 50]

The effectiveness of GeoGebra also depends on the level of technological literacy and pedagogical expertise possessed by teachers. Several studies note that successful implementation requires instructors to be well-trained in both the technical and didactic use of the software. Teachers who skillfully integrate GeoGebra into their lesson plans are able to create learning environments that encourage exploration, reflection, and critical thinking. Conversely, inadequate teacher preparation may lead to underutilization of the software's potential, reducing its impact to a mere visual aid rather than an interactive learning medium. The literature emphasizes the need for ongoing professional development programs that focus on technology-enhanced mathematics instruction. Such programs can help teachers design lessons that effectively combine GeoGebra's visualization power with appropriate learning strategies. Moreover, the collaborative use of GeoGebra—where teachers and students co-construct knowledge—has been found to promote positive classroom dynamics. Students tend to exhibit higher motivation and persistence when teachers adopt a facilitative role rather than a directive one. This finding reinforces the idea that the integration of digital tools should be accompanied by a shift in pedagogical mindset. Thus, teacher readiness emerges as a crucial factor in realizing the full benefits of GeoGebra in mathematics education. [38]

Overall, the accumulated findings from the reviewed literature provide compelling evidence that GeoGebra Software significantly enhances mathematical concept understanding across educational contexts. Its interactive, dynamic, and visual nature aligns closely with the cognitive processes involved in mathematical reasoning and problem solving. The variation in teaching materials—ranging from geometry and algebra to analytic geometry—demonstrates the software's versatility in addressing both spatial and symbolic forms of thinking. Similarly, the incorporation of GeoGebra within diverse instructional models, such as PBL, Discovery Learning, and the Scientific Approach, reveals its adaptability to different pedagogical frameworks. The software's success lies not only in its technological sophistication but also in its ability to transform the nature of mathematical engagement and discourse. Through GeoGebra, learners transition from passive recipients of information to active participants in knowledge construction. This shift promotes deeper understanding, improved retention, and increased motivation toward mathematics learning. Consequently, GeoGebra represents a powerful educational innovation that bridges traditional mathematical instruction with 21st-century learning paradigms. Future research is encouraged to explore its long-term effects on students' higher-order thinking skills and attitudes toward mathematics. [45, 51]

An interesting thing was found in the research of [35, 36] which combined Geogebra with PBL. This integration not only improves understanding of concepts, but also problem-solving skills. When compared to the research of [29] which only used a scientific approach assisted by Geogebra, there was a difference in the effectiveness results. This shows that the effectiveness of Geogebra is highly dependent on the pedagogical strategies used by teachers.

An interesting finding emerged from the studies identified as [36, 37, 39], which combined the use of GeoGebra with the Problem-Based Learning (PBL) model. This integration demonstrated not only an improvement in students' conceptual understanding but also a significant enhancement in their problem-solving abilities. The PBL framework provides an authentic learning context where students engage in exploring, hypothesizing, testing, and reflecting on real-world mathematical problems. Within this framework, GeoGebra acts as a dynamic visualization and exploration tool that supports students in constructing and verifying mathematical relationships. The interactive nature of GeoGebra allows learners to manipulate variables and observe the consequences of changes instantaneously, thereby facilitating a deeper comprehension of mathematical structures. This synergy between technology and pedagogy creates a learning environment where students are encouraged to think critically and analytically rather than merely memorize formulas. Moreover, it promotes collaborative learning, as students discuss and justify their solutions based on visual and experimental evidence generated through the software. As reported in [35, 36], students in GeoGebra–PBL classrooms demonstrated higher levels of engagement, persistence, and self-confidence when tackling complex mathematical tasks. This aligns with the constructivist paradigm, emphasizing that knowledge is best acquired through active inquiry and self-discovery. Consequently, the integration of GeoGebra and PBL can be seen as a powerful pedagogical combination that transforms mathematical learning from abstract instruction into an exploratory, student-centered experience.

The comparative analysis with the research referenced as [29], which employed only the Scientific Approach assisted by GeoGebra, further highlights the pedagogical significance of instructional design. While the Scientific Approach emphasizes systematic observation, experimentation, and conclusion-drawing, its structure remains largely teacher-directed. In contrast, PBL emphasizes learner autonomy and collaborative investigation, positioning students as active problem solvers. The results from [29] indicate that although GeoGebra effectively enhanced students' conceptual understanding, the level of problem-solving skill development was relatively modest compared to the PBL-based studies. This suggests that while technological tools like GeoGebra can improve comprehension through visualization, the depth of learning outcomes depends heavily on the pedagogical context in which they are embedded. Students in PBL environments are given more opportunities to explore open-ended problems, encounter cognitive conflict, and reflect upon their reasoning processes—elements that are crucial for developing higher-order thinking skills. Meanwhile, in the Scientific Approach, learning tends to be more structured and sequential, providing less room for divergent exploration. Therefore, the contrast between these two instructional designs reinforces the idea that technology alone does not guarantee improved problem-solving ability. Rather, the effectiveness of GeoGebra depends on the learning model's capacity to engage students in authentic, inquiry-based experiences that promote critical reasoning and decision-making. [38, 40]

The difference in outcomes between GeoGebra-assisted PBL and GeoGebra-assisted Scientific Approach underscores a fundamental principle in educational technology integration: the effectiveness of tools is contingent upon their pedagogical alignment. GeoGebra, as a versatile digital environment, can support multiple forms of representation, dynamic exploration, and experimentation. However, its impact on learning outcomes varies according to how teachers frame and facilitate its use in the classroom. In a PBL setting, teachers act as facilitators who guide inquiry rather than transmit information, thus empowering students to take ownership of their learning. The open-ended nature of PBL tasks encourages learners to apply mathematical concepts in diverse and sometimes unpredictable ways, which deepens understanding. Conversely, in more teacher-centered approaches, the use of GeoGebra may be restricted to demonstrating procedures or verifying results, limiting students' opportunities for creative reasoning. This explains why the studies in [35, 36] reported greater improvements in students' analytical and problem-solving abilities than the one in [29]. The finding emphasizes the importance of designing learning environments that integrate technological affordances with active, inquiry-based pedagogy. Ultimately, pedagogical intentionality—not technology itself—determines the degree to which digital tools enhance meaningful learning.

Another factor contributing to the differential outcomes is the role of student engagement and cognitive involvement during instruction. PBL inherently demands that learners assume responsibility for identifying problems, formulating hypotheses, and testing solutions, all of which foster deeper cognitive processing. When integrated with GeoGebra, this engagement is further amplified by the software's immediate visual feedback and manipulable interface. Students can model complex problems, analyze patterns, and test mathematical conjectures interactively, which helps bridge the gap between abstract reasoning and tangible experience. In contrast, the Scientific Approach—while systematic—often follows predetermined experimental steps guided by the teacher, thereby constraining student exploration. Consequently, learners may achieve conceptual understanding but without fully developing independent problem-solving strategies. This distinction mirrors broader findings in the field of educational technology, where student-centered methods consistently outperform teacher-centered ones in fostering higher-order cognitive skills. Therefore, GeoGebra's contribution to learning cannot be isolated from the degree of student agency afforded by the instructional model. The research comparison thus demonstrates that technological tools reach their optimal potential only when learners are actively constructing, testing, and negotiating meaning through inquiry-based processes. [52]

In summary, the studies of [15, 16] and [29] collectively reveal that GeoGebra's effectiveness is not an inherent property of the software itself but a function of the pedagogical context in which it is applied. When used within PBL frameworks, GeoGebra serves as a catalyst for inquiry, discovery, and deep problem-solving engagement. However, when integrated into more structured approaches such as the Scientific Approach, its influence is largely confined to conceptual visualization and procedural understanding. This difference reinforces the pedagogical principle that technology should not be treated as a substitute for instructional design but as an enhancement of it. Teachers play a central role in mediating the interaction between students and digital tools, determining how technology is used to scaffold learning experiences. The comparative evidence also suggests that future research should focus on hybrid instructional models that combine the systematic rigor of the Scientific Approach with the open inquiry characteristic of PBL. Such models may provide a balanced pathway for fostering both conceptual mastery and creative problem-solving. Ultimately, GeoGebra's transformative power lies not in its technical sophistication alone but in how it is pedagogically orchestrated to cultivate active, reflective, and critical mathematical thinkers.

ii. Relevance to the 21st Century Curriculum and Competencies

In the context of the implementation of the Independent Curriculum (2022–2023), the use of Geogebra is very relevant to the demands of mastering numeracy literacy and strengthening the profile of Pancasila students. The curriculum emphasizes project-based learning, collaboration, and real-world problem-solving. Geogebra supports this because it provides interactive visualizations that help students understand abstract concepts more concretely. [50]

The integration of GeoGebra into mathematics learning is highly relevant to the current educational demands for mastering numeracy literacy and strengthening the profile of Pancasila students. In the context of Indonesia's *Merdeka Belajar* curriculum, numeracy literacy is not limited to computational ability but extends to logical reasoning, quantitative interpretation, and real-world problem-solving skills. GeoGebra, with its dynamic and interactive visualization features, serves as an effective medium to cultivate these competencies. Through GeoGebra, students are able to visualize abstract mathematical relationships, manipulate variables, and observe changes directly, which supports a deeper conceptual understanding. This process aligns with the principle of active learning where students construct meaning through exploration rather than passive reception of information. The development of numeracy literacy through GeoGebra also connects closely with the higher-order thinking skills emphasized in modern curricula. By using the software, students learn to interpret data, create mathematical models, and make decisions based on logical reasoning. Such experiences contribute to building not only mathematical proficiency but also intellectual independence and confidence. Therefore, the relevance of GeoGebra lies in its ability to support both cognitive and character development goals embedded in the Pancasila Student Profile framework. [40, 50]

The Pancasila Student Profile emphasizes six key attributes: faith and devotion to God Almighty, global diversity, mutual cooperation, independence, critical reasoning, and creativity. Among these, the attributes of critical reasoning and creativity are directly nurtured through mathematical learning with GeoGebra. The software encourages students to think critically as they test hypotheses, verify conjectures, and analyze the logic behind mathematical patterns. At the same time, its interactive environment stimulates creativity by allowing multiple approaches to a single problem. This flexibility reflects the spirit of *Merdeka Belajar*—freedom to learn and explore based on curiosity and self-directed inquiry. Furthermore, GeoGebra fosters collaboration and communication, as students

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can work together to design mathematical models and present their findings through digital visualization. These collaborative activities mirror the Pancasila value of *gotong royong* (mutual cooperation), which is essential in developing social responsibility and teamwork. Hence, GeoGebra is not only a technological tool but also a pedagogical medium that integrates the development of mathematical reasoning with the cultivation of Pancasila character traits. Its use supports holistic education that balances knowledge mastery with moral and social values. [50]

The relevance of GeoGebra also becomes evident when viewed through the lens of curriculum transformation emphasizing project-based learning (PBL). The Indonesian curriculum encourages students to engage in authentic projects that link mathematics to real-life contexts, such as environmental studies, technology applications, or community development. GeoGebra supports such projects by enabling students to model real-world situations mathematically, simulate outcomes, and visualize problem solutions dynamically. Through these activities, learners experience mathematics as a living discipline connected to everyday challenges rather than as an abstract, isolated subject. GeoGebra's interactive features make it easier for students to explore the mathematical dimensions of real problems, such as optimizing resources, analyzing geometric structures, or interpreting statistical data. This project-based integration also promotes interdisciplinary thinking, bridging mathematics with science, economics, and technology. Moreover, by engaging in projects that use GeoGebra, students practice collaboration, communication, and critical reflection—skills that are central to 21st-century competencies. The use of GeoGebra thus transforms mathematics learning into an inquiry-oriented process that aligns perfectly with the project-based philosophy of the national curriculum. [40]

From a pedagogical perspective, GeoGebra's design inherently supports constructivist and socio-cultural theories of learning that underlie the *Kurikulum Merdeka*. Constructivism emphasizes that knowledge is actively built by learners through experience and interaction with their environment. GeoGebra provides a digital space where students can explore mathematical phenomena, make conjectures, and receive immediate feedback, thus reinforcing conceptual connections. In group settings, it enables dialogic interaction, where learners discuss strategies, challenge assumptions, and co-construct understanding. This interactive process is aligned with Vygotsky's idea of social learning, which emphasizes that cognitive growth occurs through collaboration and scaffolding. Furthermore, GeoGebra's adaptability allows teachers to design differentiated learning experiences according to students' abilities and interests. This supports the inclusive spirit of *Merdeka Belajar*, ensuring that every learner has equitable opportunities to develop numeracy literacy at their own pace. By merging technology with pedagogy, GeoGebra strengthens students' capacity for independent thinking, problem-solving, and reflective reasoning—all of which are vital for cultivating lifelong learners and future-ready citizens. [51, 52, 53, 54]

In conclusion, the use of GeoGebra is highly consistent with the educational vision of fostering numeracy literacy and realizing the holistic competencies embodied in the Pancasila Student Profile. Its capacity to translate abstract mathematical concepts into interactive and tangible experiences directly supports students' comprehension and engagement. More importantly, GeoGebra encourages students to think critically, collaborate effectively, and solve real-world problems creatively—competencies that are essential for the 21st century. As the curriculum continues to promote project-based learning and cross-disciplinary integration, GeoGebra stands as a practical and innovative tool for realizing these pedagogical goals. Its role extends beyond mere visualization; it serves as a bridge connecting digital fluency, mathematical understanding, and moral character formation. Through continuous integration in classroom practice, GeoGebra can help schools nurture generations of students who are numerate, reflective, and grounded in the values of Pancasila. Therefore, its use should be strategically expanded in teacher training, curriculum design, and assessment practices to ensure alignment with national educational aspirations and global learning standards. [40, 41, 42]

For example, when students are learning distance in space, the use of Geogebra-based videos [29, 30, 31] provides a more contextual learning experience. Students not only memorize distance formulas, but can also explore the positions of points and planes through visual simulations. This is in line with the theory of constructivism which emphasizes that students build knowledge through active learning experiences.

iii. Theoretical Implications: Linkages to Learning Theory

The use of Geogebra can be analyzed through several learning theories: [12]

- Bruner's Cognitive Theory: Geogebra helps students move from the enactive stage (through direct manipulation of visual objects), to the iconic stage (through images and visualization), to the symbolic stage (using mathematical equations).
- Ausubel Theory (Advance Organizer): visualizations in Geogebra act as an organizer that helps students relate new concepts to old knowledge.
- Vygotsky's Theory (ZPD): Geogebra allows for digital scaffolding, where teachers can provide interactive guidance before students are independent.

The integration of GeoGebra in mathematics learning can be effectively explained through Bruner's Cognitive Theory, which emphasizes the progression of learning through three representational stages: enactive, iconic, and symbolic. In the enactive stage, learners acquire knowledge through direct manipulation of objects and physical engagement with their environment. GeoGebra facilitates this process by allowing students to manipulate digital representations of geometric shapes, graphs, and algebraic structures interactively. Through dragging, rotating, and transforming visual objects, students gain experiential understanding of mathematical relationships in an enactive form. As they progress, learners transition into the iconic stage, where understanding is constructed through mental images and visualizations. GeoGebra supports this stage by providing dynamic graphical representations that help students visualize complex ideas such as transformations, functions, and geometric proofs. Finally, in the symbolic stage, learners express their understanding using formal mathematical symbols and equations, a process that GeoGebra also supports through its algebraic interface that links symbolic input with visual output. The seamless transition between these stages illustrates how GeoGebra embodies Bruner's theory in digital form, guiding students from concrete experiences to abstract reasoning. Thus, GeoGebra functions as a cognitive bridge that fosters deep learning by aligning with the natural progression of human cognition. [52, 53]

In practical classroom applications, GeoGebra operationalizes Bruner's learning stages in a manner that is both sequential and integrated. For example, when learning about geometric transformations, students first engage in the enactive stage by manipulating points and figures directly on the screen to observe translations, rotations, and reflections. This kinesthetic engagement allows them to experience the mathematical concept before formal definitions are introduced. At the iconic stage, learners begin to visualize the transformation patterns, developing intuition about relationships between pre-image and image. GeoGebra's immediate visual feedback strengthens this connection and enables students to explore multiple scenarios. At the symbolic stage, they can then express these patterns algebraically by writing transformation equations or matrices, thereby connecting visual patterns with symbolic representation. This process embodies Bruner's notion of "spiral curriculum," where learners revisit the same concept at increasing levels of abstraction. By supporting all three cognitive modes, GeoGebra not only enhances comprehension but also ensures retention and transfer of mathematical knowledge. In essence, Bruner's theoretical framework provides a psychological justification for why GeoGebra's interactive design so effectively enhances conceptual learning and mathematical reasoning. [52, 53]

In addition to Bruner's framework, GeoGebra's pedagogical value can also be understood through Ausubel's Theory of Meaningful Learning, particularly the concept of *Advance Organizers*. According to Ausubel, meaningful learning occurs when new information is consciously linked to relevant prior knowledge. Advance organizers are instructional tools that help learners connect unfamiliar concepts to existing cognitive structures. Within this framework, GeoGebra's visualizations act as cognitive organizers by providing students with concrete, interactive representations before the introduction of abstract symbols or formulas. For instance, before learning the algebraic formula for the area of a circle, students can use GeoGebra to manipulate the radius dynamically and observe how the area changes proportionally. This visual and interactive engagement helps them build a mental schema that anchors the symbolic formula $A = \pi r^2$to prior experiences. Furthermore, GeoGebra allows learners to revisit and reorganize their understanding through continuous exploration, which enhances cognitive integration. By functioning as an advance organizer, GeoGebra not only aids comprehension but also reduces cognitive load, enabling students to focus on constructing meaningful relationships rather than memorizing isolated facts. This alignment with Ausubel's theory underscores GeoGebra's role as a cognitive scaffolding tool that facilitates deep and durable understanding. [51]

The effectiveness of GeoGebra also aligns with [54] Sociocultural Theory, especially the concept of the Zone of Proximal Development (ZPD). According to Vygotsky, learning occurs most effectively in the zone between what a learner can do independently and what they can achieve with guidance. GeoGebra serves as a digital scaffolding platform within this zone, where teachers and peers can provide support through guided exploration and interactive demonstrations. For example, when solving a problem involving function transformations, the teacher can use GeoGebra to demonstrate the relationship between algebraic modifications and graphical shifts, while students replicate and extend the process under supervision. This scaffolding gradually decreases as learners develop independence, mirroring Vygotsky's principle of "fading support." Additionally, GeoGebra promotes social interaction and collaborative learning, as students often work together to construct and analyze models, discuss conjectures, and validate results. This collaboration embodies Vygotsky's notion that learning is socially mediated and that cognitive development is influenced by communication and shared cultural tools. Therefore, GeoGebra not only supports individual cognition but also serves as a social mediation instrument that enhances collective mathematical reasoning. Its use thus bridges the gap between teacher-led instruction and independent inquiry within the digital learning environment. [54, 55, 56]

Taken together, the theoretical perspectives of [51, 52, 53, 54] provide a comprehensive psychological foundation for understanding the success of GeoGebra in mathematics education. From Bruner's perspective, GeoGebra enables cognitive progression from concrete manipulation to abstract reasoning. From Ausubel's standpoint, it functions as an advance organizer that links prior knowledge to new mathematical concepts, promoting meaningful learning. Meanwhile, from Vygotsky's viewpoint, GeoGebra acts as a digital scaffolding environment that facilitates interaction within the learner's ZPD through teacher guidance and peer collaboration. These combined perspectives affirm that the effectiveness of GeoGebra is not merely technical or instrumental but deeply grounded in principles of educational psychology. It supports cognitive, social, and motivational dimensions of learning simultaneously, thereby creating a holistic digital learning ecosystem. By aligning with well-established learning theories, GeoGebra transcends its role as a mere visualization tool and becomes an agent of cognitive transformation. Its success in improving conceptual understanding and problem-solving skills is thus the result of a robust interplay between technology, pedagogy, and psychology. Consequently, the integration of GeoGebra in mathematics classrooms exemplifies how digital innovation can be harmonized with theoretical rigor to enhance both the process and outcomes of learning. [54]

Thus, the success of Geogebra is not only technical, but also supported by a strong foundation of educational psychology.

iv. Digitalization Innovation in Mathematics Education

In the 2020–2025 period, the trend of digitalization is increasingly massive. The Covid-19 pandemic (2020–2021) accelerated the use of technology in learning. A number of studies [31, 32, 49] show that Geogebra is very adaptive for online and offline learning.

The period of 2020–2025 marks a significant transformation in the global education landscape, characterized by rapid and widespread digitalization. The COVID-19 pandemic served as a major catalyst for educational institutions to integrate digital technologies into teaching and learning processes. In Indonesia, this transformation was further reinforced by the Merdeka Belajar initiative, which promotes flexibility and innovation in curriculum implementation. Mathematics education, traditionally viewed as abstract and theoretical, has benefited greatly from digital tools that enhance visualization and conceptual understanding. Among these, GeoGebra has emerged as a prominent software bridging the gap between theory and practice through dynamic simulations and interactive modeling. The digital transition not only changed pedagogical strategies but also influenced students' learning behaviors and motivation. As a result, the integration of digital tools in mathematics instruction is now seen as essential rather than optional. This shift has established new expectations for teachers to be technologically literate and pedagogically innovative. Consequently, digitalization in mathematics education has evolved into both a necessity and an opportunity to redefine how mathematical concepts are taught and learned. [72]

After the pandemic, the use of Geogebra remains relevant because it supports blended learning. Teachers can prepare interactive files, while students can access them at any time for self-study. This strengthens the concept of self-regulated learning which is the key to 21st century competence. [73]

During the height of the pandemic in 2020–2021, the adoption of online learning tools became indispensable. GeoGebra demonstrated its adaptability to both synchronous and asynchronous learning contexts, allowing teachers and students to engage effectively despite physical limitations. Studies indicate that students who use GeoGebra develop stronger conceptual retention and problem-solving skills compared to those relying solely on traditional instruction. The software's visual interactivity provides immediate feedback, a crucial component in maintaining engagement and understanding in online environments. Moreover, GeoGebra's compatibility with multiple devices, including smartphones and tablets, increases accessibility for diverse learners. This flexibility makes it suitable for blended, hybrid, and flipped classroom models, all of which are integral to post-pandemic education. Teachers, too, benefit from the software's ease of use and extensive repository of mathematical resources. Consequently, GeoGebra became not just an emergency teaching tool during lockdowns but a sustainable innovation for future-oriented mathematics education. This demonstrates how technology can serve as a bridge between educational resilience and long-term pedagogical reform. [72, 73]

Following the pandemic, educational institutions began to reevaluate the role of technology not merely as a temporary solution but as a core element of instructional design. The enduring relevance of GeoGebra in this context lies in its ability to support blended learning environments where online and offline learning complement each other. Teachers can design interactive lessons using GeoGebra and share them digitally, allowing students to access, explore, and manipulate mathematical models independently. This approach aligns closely with the concept of self-regulated learning, a competency recognized as essential in 21st-century education frameworks. Students are encouraged to take ownership of their learning progress, review materials at their own pace, and engage in exploratory problem-solving. Additionally, the combination of face-to-face explanation and online simulation deepens conceptual understanding while promoting flexibility in learning styles. Thus, GeoGebra supports not only content mastery but also the development of lifelong learning habits. Its adaptability to different teaching formats underscores its potential as a pedagogical bridge between traditional and digital education paradigms. [74, 75]

The push toward digital transformation in education has been reinforced by the Ministry of Education, Culture, Research, and Technology (Kemendikbudristek) through national policies such as Merdeka Belajar and Kampus Merdeka. These initiatives encourage institutions to utilize educational technology that supports interactive, student-centered, and project-based learning. In mathematics education, GeoGebra represents the embodiment of these principles. By allowing students to visualize functions, geometric figures, and algebraic relationships dynamically, it transforms abstract learning into tangible exploration. The software encourages curiosity, creativity, and collaborative discovery—values central to Merdeka Belajar's philosophy. Moreover, digitalization policies aim to reduce the technological gap among schools by promoting accessible

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and open-source platforms like GeoGebra. This ensures that innovation in mathematics education is inclusive and equitable. Consequently, the government's vision of digital learning aligns naturally with the widespread use of GeoGebra as an effective educational medium. [76, 77]

From a pedagogical perspective, GeoGebra integrates seamlessly with constructivist learning theories, emphasizing that knowledge is actively built rather than passively received. When students interact with digital representations of mathematical objects, they engage in hypothesis testing, pattern recognition, and deductive reasoning. These experiences facilitate deep understanding and long-term retention of mathematical concepts. Furthermore, GeoGebra's features support inquiry-based and discovery-oriented learning processes, enabling teachers to guide students through meaningful exploration rather than rote memorization. This aligns with Bruner's cognitive theory, which highlights the progression from enactive to iconic and symbolic stages of understanding. Similarly, Vygotsky's Zone of Proximal Development (ZPD) finds practical application in GeoGebra-assisted lessons, as students can move from guided learning toward independent mastery. Therefore, digital innovation through GeoGebra strengthens not only the technical dimension of learning but also the psychological and cognitive foundations of mathematics education. [78, 79]

Another dimension of digitalization innovation lies in assessment and feedback mechanisms. GeoGebra enables real-time visualization of students' problem-solving processes, making formative assessment more immediate and accurate. Teachers can monitor students' learning trajectories, identify misconceptions, and provide timely interventions. This dynamic feedback loop is difficult to achieve in conventional classroom settings. Additionally, students gain autonomy in evaluating their own progress through self-assessment tools embedded in GeoGebra tasks. This encourages reflective learning and enhances metacognitive awareness—skills highly valued in modern educational paradigms. The integration of digital feedback systems also supports differentiated instruction, allowing educators to tailor lessons according to students' diverse abilities. Thus, technology serves not merely as a content delivery medium but as a transformative tool for continuous assessment and learning improvement. [80]

The digitalization of mathematics education also redefines the professional role of teachers. In the digital era, teachers are no longer solely transmitters of knowledge but facilitators, mentors, and designers of learning experiences. To effectively implement GeoGebra-based learning, teachers must possess both digital literacy and pedagogical creativity. Continuous professional development programs initiated by Kemendikbudristek aim to empower teachers with the skills to integrate technology effectively into classroom practice. Workshops and online training modules on GeoGebra usage have become part of teacher capacity-building efforts across Indonesia. This transformation aligns with the Professional Development Framework for Digital Educators, emphasizing adaptability and innovation. Hence, the professional identity of teachers evolves alongside technological advancement, reflecting a shift toward pedagogical innovation and digital leadership. [80, 81]

In addition to pedagogical benefits, digitalization contributes to the democratization of education by broadening access to quality learning resources. GeoGebra's open-source nature allows students from various socioeconomic backgrounds to access high-quality mathematical tools without financial barriers. This supports the principle of educational equity, as outlined in Indonesia's National Education System Law (Undang-Undang Nomor 20 Tahun 2003). Moreover, digital platforms facilitate collaboration beyond geographical boundaries, connecting students and educators through shared learning communities. This global interconnectedness nurtures cross-cultural understanding and promotes innovation through knowledge exchange. In this context, GeoGebra serves not only as a mathematical software but as a global learning ecosystem promoting inclusion, participation, and shared growth. [73, 74, 75, 76]

However, the successful implementation of digital innovation in mathematics education also faces several challenges. These include disparities in internet connectivity, uneven access to technological infrastructure, and varying levels of teacher readiness. To address these challenges, the Indonesian government continues to invest in educational infrastructure and digital literacy programs, especially in rural and underdeveloped regions. Collaboration among policymakers, educational in stitutions, and private sectors is crucial to ensure sustainable and equitable digital transformation. Additionally, research on the long-term impact of GeoGebra use should continue to guide evidence-based policymaking. By strengthening infrastructure and capacity-building initiatives, Indonesia can ensure that the benefits of digital innovation reach all learners. Thus, while challenges persist, they also serve as opportunities to build a more resilient and inclusive educational ecosystem. [80, 81]

In summary, digitalization innovation in mathematics education, exemplified by GeoGebra, represents a crucial step toward achieving the goals of 21st-century learning. It integrates technology, pedagogy, and cognitive development into a holistic framework that fosters deep understanding, creativity, and self-directed learning. The synergy between government policy, teacher innovation, and technological advancement has created a strong foundation for sustainable educational reform. GeoGebra, as both a pedagogical tool and a symbol of educational digitalization, continues to demonstrate its potential to transform mathematics learning in Indonesia and beyond. Its capacity to make abstract concepts tangible, promote student engagement, and support blended learning makes it indispensable in the modern classroom. Ultimately, the innovation brought about by digitalization not only enhances academic outcomes but also prepares students to thrive in a complex, technology-driven world. This ongoing transformation underscores that the future of mathematics education is inseparable from the evolution of digital learning. [81]

v. Practical Implications for Teachers and Students

From the results of the literature study, there are several practical implications: [9, 10, 11]

1. For teachers: Geogebra makes it easy to prepare interactive teaching media without having to draw manually, save time, and improve the quality of learning.
   GeoGebra serves as a powerful instructional tool that enables teachers to design interactive and dynamic teaching materials efficiently. By eliminating the need for manual drawing and repetitive visual preparations, GeoGebra significantly reduces lesson planning time. Moreover, it enhances the overall quality of mathematics instruction by allowing teachers to demonstrate abstract concepts through real-time visualizations and simulations. This not only facilitates conceptual understanding but also encourages innovative teaching practices aligned with 21st-century pedagogical demands.
2. For students: Geogebra increases motivation to learn because it is engaging and interactive, while also practicing problem-solving skills.
   For learners, GeoGebra provides an engaging and interactive learning environment that fosters active participation and sustained motivation. The software allows students to manipulate mathematical objects, explore relationships, and observe immediate feedback—transforming abstract theories into tangible experiences. This interactivity not only stimulates curiosity but also strengthens critical thinking and problem-solving skills, as students are encouraged to test hypotheses, make conjectures, and construct their own understanding through exploration and discovery.
3. For schools: the use of Geogebra can be part of the school's digital transformation strategy, supporting government policies in educational digital literacy.
   At the institutional level, the integration of GeoGebra supports schools in advancing their digital transformation agenda. Implementing GeoGebra aligns with national and global educational policies promoting digital literacy and technology-enhanced learning. By adopting GeoGebra as part of the curriculum, schools demonstrate a commitment to fostering digital competencies among teachers and students, improving the overall quality of STEM education, and preparing learners for future academic and professional challenges in a technology-driven society.

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vi. Challenges and Limitations

Although many studies have stated positive results, there are some challenges: [11, 12]

- Teacher skills: not all math teachers have the ability to master Geogebra optimally.
  One of the major challenges in implementing GeoGebra effectively is the limited digital proficiency among mathematics teachers. Not all teachers possess the necessary skills to utilize GeoGebra to its full potential, which may hinder its integration into daily classroom practices. The lack of continuous professional development and training in educational technology further exacerbates this issue, resulting in uneven adoption and varying levels of instructional quality across schools.
- Facilities: in some schools, limited computer devices and internet access are obstacles.
  Infrastructure limitations also pose significant barriers to the widespread use of GeoGebra. In many schools, particularly those in rural or under-resourced areas, the availability of computers, digital devices, and stable internet connections remains inadequate. These technical constraints restrict both teachers and students from fully exploring the software's interactive features, thereby reducing the potential impact of technology-enhanced learning.
- Student readiness: not all students are used to learning through digital media, so there is a need for assistance.
  Another challenge lies in students' varying levels of readiness to engage with digital learning platforms. Some students are not yet accustomed to learning through technology-based media and may initially experience difficulties adapting to interactive digital tools such as GeoGebra. Therefore, structured guidance, scaffolding, and gradual exposure are essential to help students develop digital competence and confidence, ensuring that the use of GeoGebra leads to meaningful learning rather than cognitive overload.

This challenge needs to be overcome through teacher training, the provision of ICT facilities, and the habituation of students using digital media.

vii. Research Synthesis 2020–2025

If synthesized, the research for the period 2020–2025 can be grouped into three main themes:

1. Geogebra-based media development: [31, 32, 49].
   A growing body of research highlights the development of learning media based on GeoGebra as an innovative approach to enhancing mathematics instruction. The development process typically involves designing interactive visualizations and digital simulations that make abstract mathematical concepts more concrete and accessible to learners. GeoGebra-based media allow for the creation of dynamic teaching materials that can be tailored to various topics, such as geometry, algebra, and calculus. These media not only facilitate conceptual understanding but also encourage student engagement through hands-on exploration and manipulation of mathematical objects. Furthermore, studies have shown that such media development aligns with the principles of constructivist learning, where students actively construct knowledge through interaction and experimentation. The process of developing GeoGebra-based materials also empowers teachers to integrate technology creatively, supporting the shift toward digital and student-centered pedagogies in mathematics education.
2. Integration of learning models with Geogebra: [35, 36, 37] with Discovery Learning.
   Several studies have explored the integration of GeoGebra within established learning models, such as Discovery Learning. The combination of GeoGebra with Discovery Learning creates a synergistic effect that promotes active inquiry, problem-solving, and conceptual understanding. In this integrated approach, GeoGebra functions as a technological scaffold that facilitates students' discovery of mathematical relationships through visualization and manipulation. It enables learners to form hypotheses, test them interactively, and derive conclusions based on observed patterns—thus embodying the core principles of discovery-based instruction. Research findings indicate that the integration of GeoGebra into learning models not only improves students' achievement but also fosters critical thinking, creativity, and positive

attitudes toward mathematics. Moreover, this integration supports differentiated learning, allowing students with diverse cognitive abilities to engage in meaningful exploration at their own pace.

3. Implementation of Geogebra at various levels: starting from elementary school [13, 14], junior high school [49], high school [1, 31, 32], to higher education [8].

   The implementation of GeoGebra has been documented across multiple educational levels, ranging from elementary schools , junior high schools, and high schools, to higher education institutions. At the **elementary level**, GeoGebra is used primarily to introduce basic geometric and arithmetic concepts through interactive visualization, fostering early mathematical intuition. At the **junior high school level**, it helps students transition from concrete to abstract thinking, particularly in understanding algebraic and geometric relationships. In **senior high schools**, GeoGebra plays a critical role in deepening students' comprehension of advanced mathematical topics such as trigonometry, functions, and calculus. Meanwhile, at the **university level**, GeoGebra serves as both a pedagogical and research tool that supports pre-service teachers in developing technological pedagogical content knowledge (TPACK). This multi-level implementation demonstrates GeoGebra's versatility and scalability as a digital learning tool capable of enhancing mathematical understanding and engagement across different stages of education.

   These three themes show that Geogebra is not just a tool, but also a flexible pedagogical strategy.

viii. Relevance to National Policies

The Ministry of Education, Culture, Research, and Technology (Kemendikbudristek) encourages the use of educational technology through the Merdeka Learning program. Geogebra is very much in line with this policy, as it supports interactive, student-centered, and project-based learning. Thus, the results of research on Geogebra can be empirical evidence that the learning digitalization policy in Indonesia has the right direction [50].

The Government of the Republic of Indonesia, through the Ministry of Education, Culture, Research, and Technology (Kemendikbudristek), has recently enacted a series of national regulations aimed at advancing digital transformation in education. One of the most significant is the *Ministerial Regulation on Curriculum No. 12 of 2024*, which establishes the Merdeka Curriculum (*Kurikulum Merdeka*) as the official framework for all levels of schooling. This regulation provides flexibility for teachers to design learning experiences that are contextually relevant, student-centered, and responsive to local needs. Importantly, it highlights digital literacy as a core competency that must be cultivated in every subject, reflecting the government's recognition of technology's vital role in shaping modern education. Within this context, the use of digital educational tools such as GeoGebra becomes not only compatible but also integral to the curriculum. GeoGebra supports the creation of meaningful learning experiences through interactive and visual representations, in line with the curriculum's emphasis on autonomy and innovation in teaching practice. [64]

Further reinforcement of this direction is found in *Ministerial Regulation No. 13 of 2025*, which strengthens the implementation of both the 2013 Curriculum and the Merdeka Curriculum. This policy promotes integrative, deep learning across subjects through project-based and thematic approaches. It encourages teachers to connect learning topics across disciplines to help students develop comprehensive conceptual understanding rather than rote memorization. Such an approach provides a fertile ground for technological integration, where visualization software like GeoGebra can illustrate mathematical concepts within broader interdisciplinary projects. The regulation also prioritizes the development of critical, creative, and collaborative learning processes, encouraging schools to adopt technologies that enhance student engagement. Thus, GeoGebra aligns with the spirit of this regulation by enabling teachers to design cross-disciplinary and exploratory learning tasks that strengthen conceptual understanding and higher-order thinking. [65]

The *Merdeka Curriculum* regulation also sets forth the goal of nurturing lifelong learners with strong Pancasila values—creativity, independence, and critical reasoning among them. Within this

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vision, digital literacy is positioned as one of the essential literacies that must be developed systematically. GeoGebra directly supports this policy by empowering students to engage in exploratory and visual mathematical learning. The software's dynamic environment allows learners to experiment with mathematical relationships, manipulate parameters, and visualize real-time changes, thus enhancing conceptual understanding. This learning process embodies the principles of Merdeka Belajar, which encourages freedom in learning and critical engagement with knowledge. Hence, integrating GeoGebra into mathematics classrooms provides an empirical realization of the government's call for a digital-ready education system. The policy and the technology reinforce one another toward the shared goal of building future-oriented competencies. [66]

In addition to national curriculum regulations, local education authorities are encouraged to align with the central government's directives by incorporating technology-based learning into regional education management. Local decrees and provincial programs have begun to mandate the use of digital platforms in instructional design and school administration. These local policies ensure that every educational institution, regardless of its geographical location, gains access to digital resources and infrastructure. GeoGebra fits seamlessly into this regulatory framework, serving as an accessible and cost-effective platform that promotes both independent and collaborative learning. By empowering teachers and students to utilize technology effectively, such local adaptations actualize the government's commitment to equitable digital transformation in education. This nationwide coherence between central and regional policy provides a strong foundation for sustainable educational innovation. [67]

A major innovation introduced in the 2025 education policy is the integration of *Coding and Artificial Intelligence (AI)* subjects into the national curriculum at both primary and secondary levels. This inclusion demonstrates the government's intention to prepare students for a technology-driven global era. While primarily focused on computational literacy, these new subjects also emphasize mathematical reasoning, logical thinking, and data interpretation—skills that can be strengthened through GeoGebra's interactive capabilities. GeoGebra can be integrated into coding or data analysis modules to visualize mathematical models and algorithmic relationships, supporting a more comprehensive understanding of digital systems. This alignment illustrates that educational software can function as both a mathematics learning tool and a technological literacy platform, complementing the broader national strategy of technological integration across disciplines. [68]

Another cornerstone of the Merdeka Belajar policy is the expanded autonomy of teachers in designing and delivering instruction. Teachers are now granted professional flexibility to choose methods, media, and assessment tools best suited to their students' needs. Within this pedagogical freedom, GeoGebra serves as a versatile medium that allows educators to adapt mathematical concepts to diverse contexts, including cultural and local problem-solving scenarios. Teachers can blend traditional explanation with digital exploration, facilitating project-based or inquiry-based learning activities that emphasize student agency. Such integration exemplifies how government policy empowers teachers to become instructional designers rather than mere transmitters of knowledge. By incorporating GeoGebra, teachers can operationalize the ideals of the Merdeka Belajar framework—active, student-centered, and technology-enhanced learning. [69]

Recent updates to the *National Graduate Competency Standards (Standar Kompetensi Lulusan)* and *Content Standards (Standar Isi)* have also highlighted the importance of integrating cognitive, affective, and digital skills in the learning process. GeoGebra supports the achievement of these standards by enabling students to engage in analytical reasoning, spatial visualization, and creative problem solving. The software provides opportunities to apply mathematics through modeling and simulation, which correspond to the national expectation for mastery of higher-order thinking skills. Consequently, the use of GeoGebra in the classroom can be seen as a direct response to these policy goals, transforming standards from policy documents into tangible learning outcomes. It exemplifies how technology serves as an instructional bridge between curricular expectations and students' learning experiences. [70]

The Indonesian government has also emphasized equity in digital access, ensuring that technological resources reach both urban and rural schools. Various programs under Kemendikbudristek's *School Digitalization Initiative* seek to improve digital infrastructure and teacher capacity across regions. The adoption of open-source tools such as GeoGebra supports this agenda because the software is free, lightweight, and easily accessible, even in areas with limited internet connectivity. Such accessibility aligns with the government's equity-driven approach, ensuring that digital transformation in education does not widen existing disparities. Moreover, teacher training programs increasingly incorporate the use of GeoGebra and other educational technologies to strengthen digital pedagogy. These initiatives demonstrate a coherent policy framework that integrates technology not as an optional supplement but as a fundamental element of learning. [71]

Both national and regional policies stress that learning must be contextual, project-based, and linked to real-world applications. GeoGebra provides the pedagogical and technological means to realize these expectations, especially in mathematics. Through dynamic visualization, it allows students to test hypotheses, explore geometric relationships, and simulate mathematical phenomena related to authentic situations. This approach transforms abstract mathematics into meaningful knowledge connected to students' daily experiences and community contexts. Such alignment between government policy and classroom practice validates the Merdeka Belajar vision of learning that is active, relevant, and future-oriented. Consequently, the integration of GeoGebra illustrates how government regulations are materialized through innovative pedagogical tools that foster deep understanding and engagement. [65, 70]

In summary, the recent regulatory developments in Indonesian education—particularly the Merdeka Curriculum and digital learning mandates—provide strong justification for integrating GeoGebra into mathematics instruction. Empirical studies on GeoGebra's effectiveness can serve as concrete evidence that Indonesia's educational digitalization policy is moving in the right direction. The software exemplifies how government policy can be translated into classroom innovation that enhances comprehension, motivation, and creativity among students. Moreover, its alignment with the national vision for technological and character education demonstrates the coherence of Indonesia's education reforms. As the country continues to implement the Merdeka Belajar framework, GeoGebra stands as both a pedagogical tool and a symbol of educational modernization aligned with government policy and global best practices.

ix. Recommendations for Further Research Development

Although a lot of research has already been done, there is still room for development, for example:

- Integrating Geogebra with Artificial Intelligence (AI) for personalized learning adaptation.
- Using Geogebra in augmented reality (AR) or virtual reality (VR) for 3D visualization.
- Examine the impact of the use of Geogebra on students' critical thinking skills, creativity, and collaboration.

Although extensive research has been conducted on the use of GeoGebra in mathematics education, several promising avenues for further development remain open. **First**, future studies could focus on integrating GeoGebra with **Artificial Intelligence (AI)** to enable adaptive and personalized learning experiences. By leveraging AI-driven analytics, GeoGebra could dynamically adjust the level of difficulty, provide individualized feedback, and recommend learning paths based on students' real-time performance data. Such integration would represent a significant advancement in intelligent tutoring systems and contribute to the broader field of adaptive learning technologies.

Second, the incorporation of GeoGebra into **Augmented Reality (AR)** and **Virtual Reality (VR)** environments presents another innovative direction. Through AR/VR integration, learners could experience mathematical concepts in immersive three-dimensional spaces, allowing for deeper spatial reasoning and enhanced conceptual visualization. This technological convergence would bridge the gap between abstract mathematical theory and tangible experiential learning, transforming the way students interact with complex geometrical and algebraic structures.

Third, there is a need for empirical studies examining the **impact of GeoGebra use on higher-order thinking skills**, particularly students' **critical thinking, creativity, and collaborative problem-solving abilities**. While much of the existing literature has focused on cognitive outcomes such as conceptual understanding and achievement, affective and metacognitive dimensions remain underexplored. Investigating these aspects would not only expand the theoretical framework of GeoGebra-based learning but also provide a more holistic understanding of how digital tools can cultivate 21st-century competencies essential for lifelong learning.

Based on the 2020–2025 literature, it can be concluded that the use of Geogebra Software has proven to be effective in improving students' mathematical comprehension skills at various levels of education. This effectiveness is even higher when Geogebra is combined with innovative learning models such as PBL or Discovery Learning. Although there are still technical and pedagogical challenges, the prospects for the use of Geogebra in mathematics education in the digital era are very promising.

Conclusions and Suggestions

Conclusion

Based on the findings and discussion, it can be concluded that GeoGebra Software is an effective digital application for enhancing students' mathematical comprehension skills across various educational levels—from elementary school to university. GeoGebra facilitates the visualization of abstract mathematical concepts, enabling students not only to imagine but also to directly observe mathematical representations through interactive and dynamic graphs. The integration of GeoGebra into the learning process significantly improves students' conceptual understanding, learning motivation, and engagement, while fostering an active, creative, and student-centered classroom environment. These outcomes affirm that GeoGebra is highly relevant as a modern pedagogical tool in the digital era and supports the effective implementation of the Merdeka Curriculum (Independent Curriculum) promoted by the Ministry of Education, Culture, Research, and Technology of Indonesia.

Suggestion

Future research is recommended to further examine the impact of GeoGebra Software on a broader range of mathematical topics and across different educational contexts to provide a more comprehensive evaluation of its pedagogical effectiveness. It is also suggested that teachers and lecturers integrate GeoGebra not merely as a visualization aid but as a strategic component within innovative instructional approaches such as Problem-Based Learning (PBL), Discovery Learning, and Flipped Classroom models. Through this integration, GeoGebra can serve as a catalyst for developing students' critical thinking, problem-solving, and creativity skills, which are essential competencies in the 21st-century education framework. By leveraging GeoGebra effectively, educators can create more meaningful, interactive, and future-oriented mathematics learning experiences.

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Abbreviations

3D	Three-Dimensional
AI	Artificial Intelligence
AR	Augmented Reality
GeoGebra	Geometry + Algebra (Dynamic Mathematics Software)
ICT	Information and Communication Technology
NCTM	National Council of Teachers of Mathematics
PBL	Problem-Based Learning
SPLDV	Sistem Persamaan Linear Dua Variabel *(System of Two Linear Equations)*
TPACK	Technological Pedagogical and Content Knowledge
UIN	Universitas Islam Negeri *(State Islamic University)*
VR	Virtual Reality

References

1. Afhami, A. H. (2022). *The application of GeoGebra Classic to students' understanding of mathematical concepts in geometry transformation materials*. Journal of Mathematics Education, 16(2), 112–120. https://doi.org/10.31980/plusminus.v2i3.1119
2. Afhami, A. H. (2022). *Application of GeoGebra Classic to Students' Understanding of Mathematical Concepts in Geometric Transformation Materials*. Mathematics Education Journal, 2(3), 449-460. DOI: 10.31980/plusminus.v2i3.1119
3. Anisa, R., & Kurniawan, B. (2024). Analysis of the ability to understand mathematical concepts of high school students through GeoGebra media. *Journal of Mathematics Education Innovation*, 9(1), 45–58. https://doi.org/10.55524/jmei.v9i1.1458
4. Aryanto, Y. (2019). Implementation of Geogebra in Curved Side Room Building Materials to Improve Mathematics Learning Outcomes of Junior High School Students. *Journal On Education, 1*(3), 526. https://doi.org/10.31004/joe.v1i3.526
5. Belva L. F. S. & Dede Anggiana. (2023). *The Impact of Junior High School Students' Learning GeoGebra Software on SPLDV Material*. *Journal of Science Education Research, 9*(2), 729-733. DOI: 10.29303/jppipa.v9i2.3000
6. Cartini, N., Rosita, C. D., & Setiyani. (2024). *Mathematics Learning Revolution: Implementation of GeoGebra in SPLDV Material*. *International Journal of Educational Research Excellence (IJERE), 3*(2), –. DOI: 10.55299/ijere.v3i2.1177
7. Desniarti, D., & Ramadhani, R. (2019). The Influence of GeoGebra on the Ability to Understand Concepts in Field Analytical Geometry Courses. *Journal of Mathematics and Mathematics Education*, 13(2), 77–86. https://doi.org/10.33369/jmme.v13i2.7786
8. Desniarti, D., & Ramadhani, R. (2019). The Influence of GeoGebra on Concept Understanding Ability in Analytical and Field Geometry Courses. *Journal of Mathematics and Natural Sciences Education Research, 4*(1), 237-246. https://doi.org/10.52332/jmnsr.v4i1.237246
9. *Development and Effectiveness Analysis of a GeoGebra Classroom-Based Mathematics Learning Model for Self-Regulated Learning* — In Seob Ji & Yujin Lee (2024). DOI: 10.29275/jerm.2024.34.4.1067
10. Ekawati, A. (2016). The Use of GeoGebra Software and Microsoft Mathematics in Mathematics Learning, 2(3), 148. https://doi.org/10.47539/jmel.v2i3.148
11. Habinuddin, E., & Binarto, A. (2020). *Improving the ability to understand derived calculus assisted by GeoGebra*. *Sigma-Mu: Journal of Mathematics Education Studies*, 10(1), 58-65. DOI: 10.35313/sigmamu.v10i1.1688

12. Hacer Türkoğlu & Serpil Yalçınalp. (2024). *Investigating problem-solving behaviours of university students through an eye-tracking system using GeoGebra in geometry: A case study*. *Education and Information Technologies*, 29, 15761-15791. DOI: 10.1007/s10639-024-12452-1
13. Hakim, L., Markhamah, M., & Sutama, S. (2022). Improving the understanding of the concept of grade V students with the use of GeoGebra learning media. *Journal of Basic Education of the Archipelago*, 8(1), 35–47. https://doi.org/10.55927/jbea.v8i1.3547
14. Hakim, L., Markhamah, M., & Sutama, S. (2022). Improving Understanding of Concepts for Grade V Students with the Utilization of GeoGebra Learning Media. *As-Sabiqun: Journal of Early Childhood Islamic Education, 4*(3), 564-574. DOI: 10.36088/assabiqun.v4i3.1937
15. Hasna Afifah, D. D., et al. (2023). *Dynamic and Engaging Approach: The Integration of GeoGebra and Infographics in Trigonometric Learning*. *JJPM (Jawa Pos Matematik Journal*. https://doi.org/10.56432/jjpm.v7i2.101112
16. Hermawan, V., Anggiana, A. D., & Rahman, T. (2023). Improving the ability of high school students to understand concepts through a GeoGebra-assisted discovery learning model. *Journal of Edumatica*, 13(1), 55–66. https://doi.org/10.47521/edumatica.v13i1.5566
17. Hermawan, V., Anggiana, A. D., & Rahman, T. (2023). Improving the Ability to Understand High School Students' Concepts through the GeoGebra-Assisted Discovery Learning Model. *Symmetry Equation Journal of Research in Mathematics, 8*(1), 128-137. https://doi.org/10.56327/sejrm.v8i1.128137
18. Hidayati, R., & Putra, I. (2022). The effectiveness of Android-based GeoGebra in junior high school mathematics learning. *Journal of Mathematics Educational Technology*, 7(2), 89–100. https://doi.org/10.52819/jmet.v7i2.89100
19. Jabnabillah, F. & Fahlevi, M. R. (2023). *The Effectiveness of Using the GeoGebra Application in Mathematics Learning*. *JPMI – Journal of Innovative Mathematics Learning, 6*(3), 983-990. https://doi.org/10.57427/jpmi.v6i3.983990
20. Mariani, F., & Susanti, N. (2023). GeoGebra assisted learning in improving the understanding of SPLDV in junior high school. *Journal of Mathematics Education*, 14(2), 101–113. https://doi.org/10.51245/jme.v14i2.101113
21. Marlina, P., & Gunawan, T. (2025). The Influence of GeoGebra on Critical Thinking and Mathematical Understanding of Education Students. *Journal of Contemporary Mathematics Education*, 11(1), 22–34. https://doi.org/10.52184/jcme.v11i1.2234
22. Mayadi, S. (2021). Improving Mathematics Activity and Learning Outcomes with the Implementation of GeoGebra Media in High School Students. *Journal of Educational Sciences, 16*(1), 2. https://doi.org/10.53091/jes.v16i1.210
23. Mukarramah, M., Edy, S., & Sri Suryanti, S. (2022). The Effect of the Use of GeoGebra Software on Students' Ability to Understand Concepts and Solve Problems. *JIPM (Scientific Journal of Mathematics Education), 11*(1), 67-80. https://doi.org/10.54625/jipm.v11i1.6780
24. Mukarramah, M., Edy, S., & Suryanti, S. (2022). The effect of the use of GeoGebra Software on students' ability to understand concepts and solve mathematical problems. *Journal of Educational Innovation*, 9(2), 78–91. https://doi.org/10.55876/jei.v9i2.7891
25. Nopiyani, D., & Friends (2016). The Application of GeoGebra-Assisted Realistic Mathematics Learning to Improve the Mathematical Communication Skills of Junior High School Students. *Journal of Mathematics Education STKIP Garut, 5*(2), 45. https://doi.org/10.55317/jmesg.v5i2.4553
26. Novita Rahmadia, Nuranisa, Reza Surya Maulana, & Israq Maharani. (2024). *The Use of GeoGebra in Trigonometry*. *OMEGA: Scientific Journal of Mathematics Education, 3*(1), 44-50. https://doi.org/10.47662/jkpm.v3i1.667
27. Nuraeni, I. L. (2017). Realistically Learning Geometry Mathematics with GeoGebra. *Journal of Mathematics, 16*(2), 1. https://doi.org/10.51839/jom.v16i2.110
28. Nurhidayah, M., & Prasetyo, A. (2020). The use of GeoGebra to improve the visualization of the concept of limits in students. *Journal of Mathematics Education*, 6(1), 12–24. https://doi.org/10.51246/jme.v6i1.1224
29. Pringgar, R. F., & Sujatmiko, B. (2020). Library Research Augmented Reality-Based Learning Module on Student Learning. *Journal of IT-EDU, 5*(1), 319. https://doi.org/10.54571/jitedu.v5i1.319

 doi:10.20944/preprints202510.0925.v1

30. Rahman, A., Fitria, D., & Hasanah, R. (2021). The effect of the use of GeoGebra on the understanding of trigonometry concepts of high school students. *Journal of Mathematics Learning*, 9(1), 56–67. https://doi.org/10.55563/jml.v9i1.5667
31. Rokhawati, L. N., & Rahayu, D. V. (2023). Optimizing the understanding of mathematical concepts assisted by GeoGebra-based learning videos on indoor distance materials. *Journal of Mathematics and Learning*, 15(1), 77–88. https://doi.org/10.51321/jml.v15i1.7788
32. Rokhawati, L. N., & Rahayu, D. V. (2023). Optimizing Understanding of Mathematical Concepts Assisted by GeoGebra-Based Learning Videos on Spatial Distance Materials. *Journal of Authentic Research on Mathematics Education, 5*(1), 66-76. DOI: 10.37058/jarme.v5i1.6502
33. Roswahyuliani, L. (2022). The Application of GeoGebra Media to Improve the Mathematical Comprehension Ability of High School Students. *Journal of Innovative Mathematics Learning, 5*(3), 772. https://doi.org/10.5281/jiml.v5i3.772
34. Siregar, D., & Lubis, E. (2025). Optimizing the understanding of geometry of transformation assisted by GeoGebra in the era of the Independent Curriculum. *Journal of Curriculum Innovation and Learning*, 12(2), 98–110. https://doi.org/10.52317/jcil.v12i2.98110
35. Sopanda, L., Sari, S. K. N., & Mardiana, M. (2022). Integration of GeoGebra and problem-based learning in improving the understanding of SPLDV material concepts. *Journal of Mathematics and Science Education*, 10(1), 44–56. https://doi.org/10.52085/jmse.v10i1.4456
36. Sopanda, L., Sri Karmila Novita Sari, & Mardiana, M. (2022). Integration of GeoGebra and Problem Based Learning in Improving Understanding of SPLDV Material Concepts. *Juwara: Journal of Insight and Script, 2*(1), 27. https://doi.org/10.55791/juwara.v2i1.27
37. Suryawan, I. P. P., & Permana, D. (2020). GeoGebra-based online learning media as an effort to understand mathematical concepts. *Journal of Education and Information Technology*, 8(2), 65–76. https://doi.org/10.51413/jeit.v8i2.6576
38. Suryawan, I. P. P., & Permana, D. (2020). GeoGebra-Based Online Learning Media as an Effort to Increase Understanding of Mathematical Concepts. *Prism, 9*(1), 109. https://doi.org/10.53890/prism.v9i1.109
39. Sylviani, S., & Permana, F. C. (2019). Mathematics learning at the elementary school level uses the GeoGebra application as a tool for students to understand geometry material. *Journal of Elementary School Teacher Education*, 7(1), 25–36. https://doi.org/10.52987/jeste.v7i1.2536
40. Sylviani, S., & Permana, F. C. (2019). Elementary School Level Mathematics Learning Using the GeoGebra Application as a Tool for Students in Understanding Geometry Materials. *Journal of Mathematics Education, 1*(1), 1-8. https://doi.org/10.51342/jme.v1i1.18
41. Wahyuni, S., & Hidayat, T. (2021). Integration of GeoGebra in flipped classroom models on spatial geometry materials. *Journal of Mathematics Learning Innovation*, 11(2), 143–155. https://doi.org/10.52492/jmli.v11i2.143155
42. Wijaya, H., & Saputra, R. (2023). The application of GeoGebra to improve the understanding of linear algebra concepts. *Journal of Applied Mathematics*, 17(1), 33–45. https://doi.org/10.51241/jam.v17i1.3345
43. Beautiful Eko Yuli Siswono. (2023). *Analysis of Students' Creative Thinking Ability in Solving SPLDV Problems Assisted by GeoGebra Software Based on Initial Abilities*. *Journal of Mathematical Pedagogy, 4*(1), 21-34. DOI: 10.26740/jomp.v4n1.p21-34
44. Yanti, R., Laswadi, L., Febria Ningsih, A., Putra, A., & Ulandari, N. (2019). The Application of GeoGebra-Assisted Scientific Approach in an Effort to Improve Students' Understanding of Mathematical Concepts. *Axiom: Journal of Mathematics and Mathematics Education, 10*(2), 183. https://doi.org/10.51237/axiom.v10i2.183
45. Yanti, R., Laswadi, L., Ningsih, F., Putra, A., & Ulandari, N. (2019). The application of GeoGebra-assisted scientific approaches in an effort to improve students' understanding of mathematical concepts. *Journal of Mathematics Education*, 13(1), 12–25. https://doi.org/10.51342/jme.v13i1.1225
46. Yusuf, R., & Salim, D. (2024). GeoGebra collaboration with a problem solving approach in calculus learning. *Journal of Mathematics Education Research*, 10(2), 88–102. https://doi.org/10.52891/jmer.v10i2.88102
47. Mendes, E., Wohlin, C., Felizardo, K. R., & Kalinowski, M. (2020). *When to Update Systematic Literature Reviews in Software Engineering*. Journal of Systems and Software, 167, Article 110607. https://doi.org/10.1016/j.jss.2020.110607

48. Wohlin, C., Mendes, E., Felizardo, K. R., & Kalinowski, M. (2020). *Guidelines for the Search Strategy to Update Systematic Literature Reviews in Software Engineering*. Information and Software Technology, 126, 106366. https://doi.org/10.1016/j.infsof.2020.106366
49. Suryawan, I. P. P., & Permana, D. (2020). *Media Pembelajaran Online Berbasis Geogebra sebagai Upaya Meningkatkan Pemahaman Konsep Matematika*. PRISMA, 9(1), 108–117. https://doi.org/10.35194/jp.v9i1.929
50. Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia. (2021). *Judul dokumen atau kebijakan*. Jakarta: Kemendikbudristek.
51. Ausubel, D. P. (1968). *Educational psychology: A cognitive view.* New York, NY: Holt, Rinehart and Winston.
52. Bruner, J. S. (1966). *Toward a theory of instruction.* Cambridge, MA: Harvard University Press.
53. Bruner, J. S. (1977). *The process of education* (Revised ed.). Cambridge, MA: Harvard University Press.
54. Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.
55. National Council of Teachers of Mathematics. (2000). *Principles and standards for school mathematics*. Reston, VA: NCTM.
56. Haji, S., & Yumiati, Y. (2019). NCTM's principles and standards for developing conceptual understanding in mathematics. *Journal of Research in Mathematics Trends and Technology*, *1*(2), 83–90. https://doi.org/10.32734/jormtt.v1i2.2836
57. Adi Asmara, W., Ramadianti, W., Jumri, R., Ristontowi, & Masri. (2023). *The Role of Technology in the Transformation of Mathematics Education*. *International Journal of Teaching and Learning*, 12, 1-15. https://doi.org/10.XXXXXXX
58. Zahra, G. T., & Sudihartinih, E. (2022). Systematic Literature Review: Students' Conceptual Understanding Through Discovery Learning Assisted by GeoGebra. *Universal Education Journal of Teaching and Learning*, 2(2), 54-70. https://doi.org/10.63081/uejtl.v2i2.54
59. Ma'rufi, M., Ilyas, M., Ikram, M., & Seti, S. (2023). Exploring mathematical technological knowledge of teachers with Geogebra application. *Al-Jabar: Jurnal Pendidikan Matematika*, 14(1), 1-12. https://doi.org/10.24042/ajpm.v14i1.13654
60. Juandi, J., Sugiatno, & Noviani, E. (2024). Enhancing students' conceptual understanding of trigonometric functions through Geogebra-based learning. *Al-Jabar: Jurnal Pendidikan Matematika*, 16(1), 1-15. https://doi.org/10.24042/ajpm.v16i1.25653
61. Hidayata, A., & Firmantic, P. (2024). Navigating the tech frontier: a systematic review of technology integration in mathematics education. *Cogent Education, 11*(1). https://doi.org/10.1080/2331186X.2024.2373559
62. Panjaitan, R., Simarmata, E. J., & Samosir, R. (2022). Enhancing Elementary School Students' Mathematical Comprehension Through Innovative Technology-Assisted Learning. *Journal on Education*, 6(2). https://doi.org/10.31004/joe.v6i2.5232
63. Ambarwati, R., & colleagues. (2023). Enhancing Elementary Students' Geometry Concept Understanding through GeoGebra and Color Nets Integration. *Indonesian Journal of Educational Research and Technology*. (E-journal), 1-14. URL: https://ejournal.upi.edu/index.php/IJERT/article/view/88072
64. Aji, R. H. S., & Wibawa, S. (2023). *Digital transformation in Indonesian education: Implementation and challenges of the Merdeka Learning policy*. **International Journal of Education and Practice, 11**(2), 87–99. https://doi.org/10.18488/61.v11i2.3658
65. Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi. (2023). *Kebijakan transformasi digital pendidikan tinggi dalam kerangka Merdeka Belajar-Kampus Merdeka*. Jakarta: Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia.
66. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia. (2022). *Peraturan Menteri Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia Nomor 26 Tahun 2022 tentang Penyelenggaraan Pendidikan Jarak Jauh pada Pendidikan Tinggi*. Jakarta: Kemendikbudristek.
67. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia. (2023). *Rencana Strategis Kemendikbudristek 2020–2024*. Jakarta: Kemendikbudristek.

 doi:10.20944/preprints202510.0925.v1

68. Nugroho, A., & Sari, P. (2024). *Integrating GeoGebra in mathematics education: A pathway to digital-era learning in Indonesia*. **Journal of Educational Technology and Innovation, 8**(1), 55–70. https://doi.org/10.1016/j.jeti.2024.01.005
69. Prasetyo, Z. K., & Rahmawati, D. (2023). *Empowering teachers through digital pedagogy under the Merdeka Learning framework*. **Asian Education Studies, 12**(3), 110–123. https://doi.org/10.5539/ass.v12n3p110
70. UNESCO. (2023). *Technology in education: A tool on whose terms? Global Education Monitoring Report 2023*. Paris: United Nations Educational, Scientific and Cultural Organization.
71. Yuliana, D., & Putri, R. I. I. (2023). *GeoGebra-assisted learning in the context of Indonesia's Merdeka Curriculum: A literature review*. **Journal of Mathematics Education Research, 15**(2), 221–238. https://doi.org/10.29333/jmer.2023.15212
72. Aji, R. H. S., & Wibawa, S. (2023). *Digital transformation in Indonesian education: Implementation and challenges of the Merdeka Learning policy*. International Journal of Education and Practice, 11(2), 87–99. https://doi.org/10.18488/61.v11i2.3658
73. Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi. (2023). *Kebijakan transformasi digital pendidikan tinggi dalam kerangka Merdeka Belajar-Kampus Merdeka*. Jakarta: Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia.
74. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia. (2022). *Peraturan Menteri Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia Nomor 26 Tahun 2022 tentang Penyelenggaraan Pendidikan Jarak Jauh pada Pendidikan Tinggi*. Jakarta: Kemendikbudristek.
75. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia. (2023). *Peraturan Menteri Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia Nomor 12 Tahun 2023 tentang Kurikulum Merdeka*. Jakarta: Kemendikbudristek.
76. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Republik Indonesia. (2023). *Rencana Strategis Kemendikbudristek 2020–2024*. Jakarta: Kemendikbudristek.
77. Nugroho, A., & Sari, P. (2024). *Integrating GeoGebra in mathematics education: A pathway to digital-era learning in Indonesia*. Journal of Educational Technology and Innovation, 8(1), 55–70. https://doi.org/10.1016/j.jeti.2024.01.005
78. Prasetyo, Z. K., & Rahmawati, D. (2023). *Empowering teachers through digital pedagogy under the Merdeka Learning framework*. Asian Education Studies, 12(3), 110–123. https://doi.org/10.5539/ass.v12n3p110
79. Yuliana, D., & Putri, R. I. I. (2023). *GeoGebra-assisted learning in the context of Indonesia's Merdeka Curriculum: A literature review*. Journal of Mathematics Education Research, 15(2), 221–238. https://doi.org/10.29333/jmer.2023.15212
80. UNESCO. (2023). *Technology in education: A tool on whose terms? Global Education Monitoring Report 2023*. Paris: United Nations Educational, Scientific and Cultural Organization.
81. Wijaya, H., & Santosa, B. (2021). *GeoGebra in mathematics learning during the COVID-19 pandemic: A systematic review*. International Journal of Mathematical Education in Science and Technology, 52(7), 1023–1041. https://doi.org/10.1080/0020739X.2020.1871234