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Meta-Analysis of the Effect of Realistic Mathematics Education Supported by Mathematical Software on Students's Mathematical Ability

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ABSTRACT. Mathematics education continues to seek practical instructional approaches that enhance students' conceptual understanding and foster problem-solving abilities through creative and critical thinking, aligned with Bloom's Taxonomy of Educational Objectives. This study contributes novel insights by integrating Realistic Mathematics Education (RME) supported by mathematics software within a meta-analytic framework, thereby providing a comprehensive examination of their combined effects and magnitude. The purpose of this meta-analysis was to investigate the overall impact of RME supported by mathematics software on students' mathematical abilities across multiple empirical studies. The analysis was conducted using peer-reviewed articles published in reputable international journals, with inclusion criteria based on research design, sample characteristics, and intervention features. A total of 14 studies met the eligibility criteria and were included in the analysis. Statistical procedures were employed to calculate effect sizes, assess heterogeneity, examine potential moderating variables, and determine them. Although the study was limited by the availability of high-quality empirical research and the potential for publication bias, the results provide robust evidence that integrating RME and mathematics software significantly increases students' mathematical abilities. These findings underscore the importance of technology-enhanced pedagogical strategies and offer valuable implications for educators, researchers, and policymakers seeking to advance the quality of mathematics education.

Keywords: mathematical ability; mathematics software; meta-analysis; realistic mathematics education; technology-enhanced education

ABSTRAK. Pendidikan matematika terus mencari pendekatan efektif yang tidak hanya meningkatkan pemahaman konseptual siswa tetapi juga mengembangkan keterampilan pemecahan masalah. Studi ini memberikan kebaruan dengan mengintegrasikan Pendidikan Matematika Realistis (RME) dengan dukungan perangkat lunak matematika ke dalam kerangka meta-analisis, yang menawarkan perspektif komprehensif tentang efek gabungannya. Tujuan penelitian ini adalah untuk menyelidiki dampak keseluruhan RME yang didukung oleh perangkat lunak matematika terhadap kemampuan matematika siswa di berbagai studi. Meta-analisis dilakukan menggunakan artikel empiris terpilih yang diterbitkan dalam jurnal terkemuka, dengan kriteria inklusi berdasarkan desain penelitian, karakteristik sampel, dan detail intervensi. Prosedur tersebut menghasilkan 14 artikel yang layak dianalisis. Data dianalisis menggunakan teknik statistik untuk menghitung ukuran efek, heterogenitas, dan variabel moderator potensial. Namun, studi ini dibatasi oleh ketersediaan studi empiris berkualitas tinggi dan potensi bias publikasi. Terlepas dari keterbatasan ini, temuan ini memberikan bukti kuat bahwa integrasi RME dan perangkat lunak matematika secara signifikan meningkatkan kemampuan matematis siswa. Lebih lanjut, hasil ini menyoroti pentingnya mengadopsi strategi pedagogi berbasis teknologi, yang menawarkan implikasi berharga bagi para pendidik, peneliti, dan pembuat kebijakan dalam memajukan pendidikan matematika.

Kata kunci: kemampuan matematika; meta-analisis; pendidikan berbasis teknologi; pendidikan matematika realistis; perangkat lunak matematika

INTRODUCTION

Mathematics is a fundamental discipline that plays a vital role in developing students' logical reasoning, problem-solving, and capacity to analyse real-world situations. Through mathematics learning, students are expected to think systematically, critically, and rationally when dealing with various problems. However, despite its significant role, mathematics is often perceived by students as an abstract, complex subject that is distant from everyday life (Bolstad, 2021). This negative perception causes many students to experience difficulties and show a lack of interest in learning mathematics.

Such perceptions contribute to students' low motivation and academic achievement, which may ultimately affect their long-term success in mathematics learning. Therefore, serious efforts are needed to address this challenge by developing and implementing innovative pedagogical approaches that make mathematics more meaningful and easier for students to understand. One promising approach that has received widespread attention is Realistic Mathematics Education (RME). Rooted in the ideas of Hans Freudenthal, RME emphasises the use of real-world contexts and problems as the starting point for learning, helping students construct mathematical understanding (Samura et al., 2022; Zulkardi et al., 2020).

Rather than viewing mathematics as a set of abstract rules and procedures, RME encourages students to mathematise realistic situations. This process can foster deeper conceptual understanding and develop students' critical thinking skills (Juandi et al., 2022; Lestari et al., 2023). This approach has great potential to bridge the gap between abstract mathematical concepts and students' real-life experiences.

In addition, the integration of mathematics software and digital technology has brought significant changes to mathematics education (Juandi et al., 2021; Kusumah et al., 2020; Nurjanah et al., 2020; Tamur, Juandi, & Kusumah, 2020; Tamur et al., 2022; Tamur, Ndiung, Weinhandl, et al., 2023). Software such as GeoGebra, Cabri, and Mathematica provides dynamic visualisations, interactive simulations, augmented reality (AR), and instant feedback, enriching the learning process. With the support of these technologies, students can explore mathematical structures more deeply, thereby enhancing engagement, accuracy, and understanding of mathematical concepts.

The combination of Realistic Mathematics Education (RME) and the use of mathematics software creates an effective synergy in improving the quality of mathematics learning. RME situates the learning process within contexts that are relevant and meaningful to students, thereby helping them connect mathematical concepts with real-life situations. Meanwhile, mathematics software serves as a supportive tool that enables students to explore patterns, test conjectures, and visualise abstract concepts (Sudirman et al., 2020; Tamur, 2023; Tamur et al., 2025; Tamur, Ndiung, Kurnila, et al., 2023).

By integrating these two strategies, mathematics learning can enhance both students' procedural fluency and conceptual understanding. The resulting learning environment becomes more balanced, interactive, and rich in learning experiences. The integration of RME and mathematics software also has the potential to transform mathematics learning into an engaging, student-centred process that supports long-term learning outcomes.

However, although numerous individual studies have investigated the effects of RME, with or without digital support, their findings are often fragmented and vary across contexts. Some studies report significant improvements in students' problem-solving and reasoning skills, while others note more moderate effects. Differences in study design, sample size, cultural context, and software type further complicate the interpretation of the results. These inconsistencies highlight the need for a systematic synthesis of evidence to determine the overall effectiveness of RME supported by mathematics software.

Meta-analysis offers a rigorous method for synthesizing findings across multiple empirical studies (Juandi & Tamur, 2020, 2021; Pigott & Polanin, 2020; Tamur, Juandi, et al., 2023). By calculating and combining effect sizes, meta-analysis provides a more precise estimate of the actual impact of an educational intervention. Meta-analysis also allows researchers to identify moderating factors, such as students' grade level, the type of mathematical ability measured, or the specific digital tools used. Therefore, this methodology is well-suited to assessing the effects of RME supported by mathematics software on student achievement.

Previous meta-analyses in mathematics education have examined various teaching strategies, such as cooperative learning, inquiry-based learning, and technology integration (Turgut & Turgut, 2018). These studies consistently highlight the benefits of innovative, student-centered pedagogies (Tamur & Juandi, 2020). However, the unique integration of RME with mathematics software has not been adequately synthesized within a meta-analytic framework. This creates a gap in the literature, limiting theoretical Development and classroom application.

Furthermore, the growing emphasis on 21st-century learning highlights the importance of *learning how to learn* and fostering students' engagement and enjoyment in mathematics within the digital era. This shift requires students not only to acquire mathematical competencies encompassing knowledge, skills, and attitudes aligned with the cognitive, affective, and psychomotor domains of Bloom's Taxonomy but also to develop higher-order thinking skills such as analysis, evaluation, and creation through the meaningful use of digital technologies (Tamur, 2023). Mathematics instruction that integrates Realistic Mathematics Education (RME) with mathematical software addresses these dual objectives by promoting creative and critical thinking, facilitating problem-solving grounded in real-life contexts, and enhancing students' digital literacy. Through such integration, learners progress beyond lower-order cognitive processes toward higher levels of Bloom's Taxonomy while actively engaging with authentic mathematical situations supported by technology (Juandi et al., 2022; Zulkardi et al., 2020). These competencies are crucial in preparing students to excel in higher education, the workforce, and active participation in a technology-driven society (Kusumah et al., 2020; Tamur, 2021; Tamur, Ndiung, Weinhandl, et al., 2023; Tamur et al., 2025).

Culturally responsive and contextually relevant mathematics education has become an increasingly urgent need. In many countries, mathematics instruction is still dominated by procedural approaches that emphasise memorisation of problem-solving steps without clear connections to students' real-life experiences. This condition causes mathematics learning to feel disconnected from everyday life, thereby contributing to low student engagement and the emergence of achievement gaps. When students are unable to perceive the relevance of mathematics to the realities they face, their motivation and conceptual understanding tend to decline.

Realistic Mathematics Education (RME) emerges as an approach capable of addressing this issue by situating the learning process in realistic and meaningful contexts. At the same time, the use of mathematical software provides students with opportunities to engage in exploration, visualisation, and personalised learning tailored to their needs and abilities. The combination of these two approaches has the potential to enhance Equity and improve the overall quality of mathematics education.

Based on these considerations, this study conducted a meta-analysis to examine the effects of implementing Realistic Mathematics Education supported by mathematics software on students' mathematical abilities. This study aims to estimate the overall effect size, identify influential moderator variables, and present a comprehensive synthesis of previous research. The findings are expected to contribute both empirical evidence and theoretical insights, as well as to inform educators, curriculum developers, and policymakers in designing technology-based mathematics instruction that promotes deeper learning and improved student achievement.

METHOD

This study used a meta-analysis to synthesise findings from empirical studies investigating the impact of Realistic Mathematics Education (RME) supported by mathematical software on students' mathematical abilities. Meta-analysis was chosen because it allows for the systematic combination of results from multiple studies (Juandi & Tamur, 2020; Pigott & Polanin, 2020), resulting in a more accurate estimate of the overall effect size (Juandi et al., 2021; Tamur, Juandi, & Kusumah, 2020; Wijaya et al., 2022).

The data sources consisted of articles published in international and national peer-reviewed empirical journals, conference proceedings, and dissertations between 2015 and 2025. The search was conducted using academic databases such as Scopus, Web of Science, ERIC, and Google Scholar, with keywords including "Realistic Mathematics Education," "RME," "mathematics software," "digital tools," "technology," "student achievement," and "mathematics." Additional studies were identified through the reference lists of relevant publications to ensure comprehensive coverage.

The inclusion criteria for study selection were as follows: (1) the study explicitly implemented RME combined with mathematics software as an instructional intervention; (2) the participants were students at the elementary, secondary, and tertiary education level; (3) the study reported quantitative data on students' mathematics abilities, such as comprehension, communication, problem-solving, reasoning, representation, critical and creative thinking; (4) sufficient statistical information was provided to calculate effect sizes and magnitude (e.g., mean, standard deviation, sample size, t-value, or F-value). and (5) publications written in English and Indonesian. Exclusion criteria included theoretical articles, qualitative studies without statistical data, duplicate reports of the same data set, and development studies. Furthermore, this analysis adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigour and transparency. Figure 1 presents the data screening process.

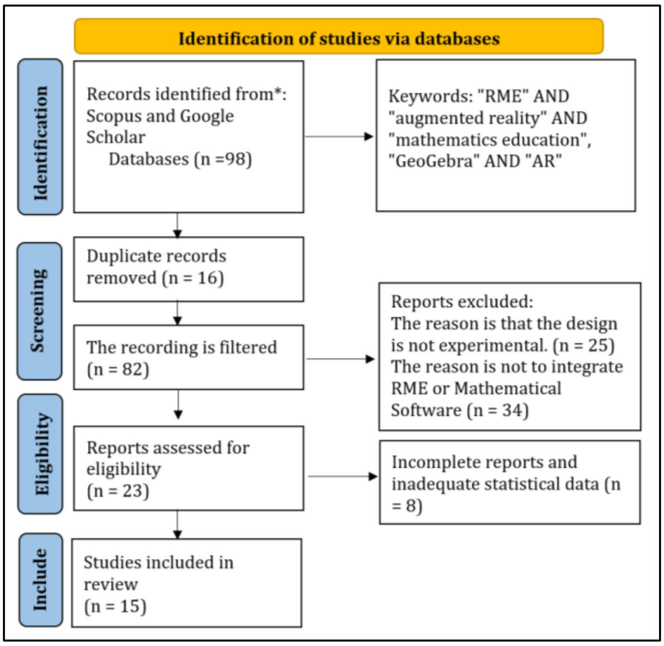


Figure 1. PRISMA Procedure

A coding protocol was developed to extract relevant information from each study, including author(s), year of publication, sample size, educational level, type of mathematical ability assessed, type of software used, study design, subject matter, and statistical data. To ensure reliability, coding was conducted independently by two researchers, and discrepancies were resolved through discussion. Inter-rater reliability was calculated using Cohen's kappa to ensure consistency in coding decisions. The level of agreement between the two coders was determined by randomly selecting 5 of the 14 duplicate primary studies and distributing them to both coders. The level of agreement between the two coders was determined using the Cohen's kappa formula as presented in equation 1 (McHugh, 2012).

$$k = \frac{Pr(a)-Pr(e)}{Pr(e)} \qquad (1)$$

Based on equation (1), Pr(a) describes the proportion of actual observed conformity, while Pr(e) reflects the proportion of conformity that occurs due to chance factors. Referring to (McHugh, 2012) criteria, an index value ≥ 0.85 indicate a high level of conformity. The calculation results show a k value of 0.91, which means substantial agreement between the two assessors, so that the developed instrument can be declared to have adequate validity.

Effect sizes were calculated using the Hedges' g formula, which corrects for bias in Cohen's d, the standardised mean difference between the experimental and control groups (Juandi et al., 2023; Tamur et al., 2021; Tamur, Komaladewi, et al., 2024). For studies reporting multiple outcomes, effect sizes were calculated separately and then aggregated. Statistical analyses were performed using Comprehensive Meta-Analysis (CMA) software, which allows calculation of overall mean effect sizes, confidence intervals, and heterogeneity indices (Q and I^2). To explore potential moderating variables, subgroup analyses and meta-regression were performed based on factors such as educational level (primary, secondary, tertiary), type of mathematical ability measured, and type of software used. Publication bias was assessed using funnel plots and Egger's regression test; minimal publication bias was considered if the p-value was > 0.05.

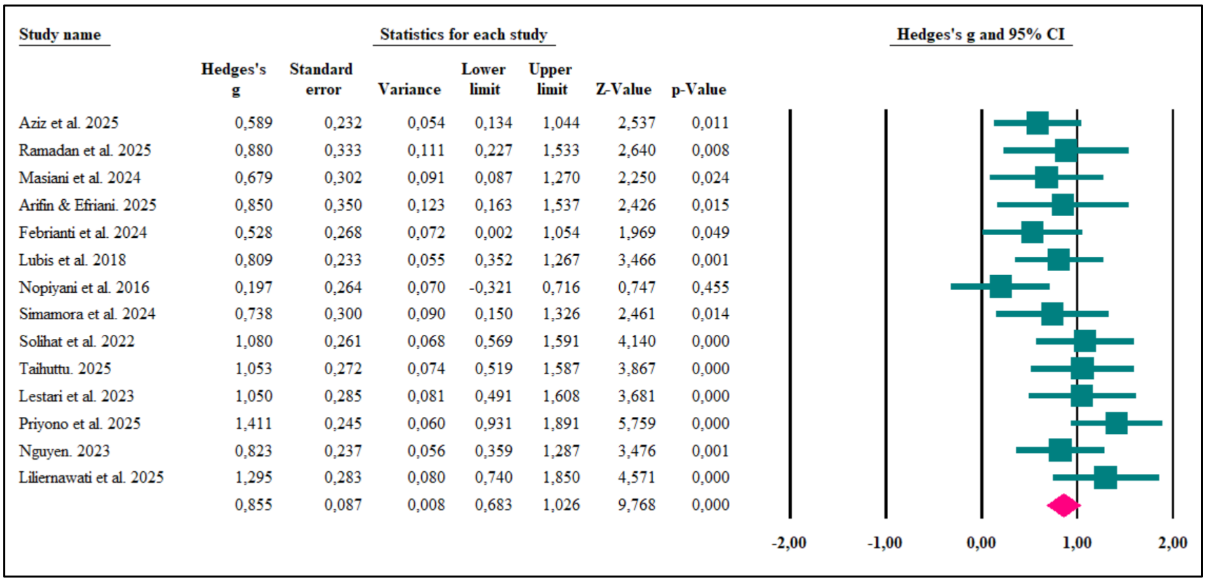
RESULTS AND DISCUSSION

This meta-analysis synthesises data from 14 empirical studies examining the effects of Realistic Mathematics Education (RME) supported by mathematical software on students' mathematical abilities. The studies included in the analysis are presented in Table 1 below.

Table 1. Studies Included in the Analysis

Author, Year	Educational level	Types of Mathematical Software
(Aziz et al., 2025)	Senior High School	Geogebra
(Ramadan et al., 2025)	Elementary school	Augmented Reality
(Masiani et al., 2024)	Senior High School	Geogebra
(Arifin & Efriani, 2025)	Junior High School	Augmented Reality
(Febrian ti et al., 2024)	Junior High School	Geogebra
(Lubis et al., 2018)	Senior High School	Geogebra
(Nopiyani et al., 2016)	Junior High School	Geogebra
(Simamora et al., 2024)	Junior High School	Geogebra
(Solihat et al., 2022)	Junior High School	Geogebra
(Taihuttu, 2025)	Junior High School	Geogebra
(Lestari et al., 2023)	Junior High School	Geogebra
(Priyono et al., 2025)	Elementary school	Augmented Reality
(Nguyen, 2023)	Senior High School	Geogebra
(Liliernawati et al., 2025)	Elementary school	Augmented Reality

When Table 1 is evaluated, it is seen that the data included in the analysis were published between 2016 and 2025. Studies on the effects of RME software were conducted at the elementary, middle, and high school levels using GeoGebra and Augmented Reality (AR) applications. The calculated effect sizes (Hedges' g) for the included studies ranged from 0.5 to 1.42, indicating a positive effect of applying RME software on students' mathematical abilities. A summary of the analysis results, showing the effect size for each study, is presented in a forest plot in Figure 2 below.



Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Aziz et al. 2025	0,589	0,232	0,054	0,134	1,044	2,537	0,011
Ramadan et al. 2025	0,880	0,333	0,111	0,227	1,533	2,640	0,008
Masiani et al. 2024	0,679	0,302	0,091	0,087	1,270	2,250	0,024
Arifin & Efriani. 2025	0,850	0,350	0,123	0,163	1,537	2,426	0,015
Febrianti et al. 2024	0,528	0,268	0,072	0,002	1,054	1,969	0,049
Lubis et al. 2018	0,809	0,233	0,055	0,352	1,267	3,466	0,001
Nopiyani et al. 2016	0,197	0,264	0,070	-0,321	0,716	0,747	0,455
Simamora et al. 2024	0,738	0,300	0,090	0,150	1,326	2,461	0,014
Solihat et al. 2022	1,080	0,261	0,068	0,569	1,591	4,140	0,000
Taihuttu. 2025	1,053	0,272	0,074	0,519	1,587	3,867	0,000
Lestari et al. 2023	1,050	0,285	0,081	0,491	1,608	3,681	0,000
Priyono et al. 2025	1,411	0,245	0,060	0,931	1,891	5,759	0,000
Nguyen. 2023	0,823	0,237	0,056	0,359	1,287	3,476	0,001
Liliernawati et al. 2025	1,295	0,283	0,080	0,740	1,850	4,571	0,000
	0,855	0,087	0,008	0,683	1,026	9,768	0,000

Figure 2. Research Forest Plot

From the illustration of the study effect sizes in Figure 2, it is clear that the horizontal lines (95% CIs) for each study differ. This indicates the uncertainty range of the estimates. It is also apparent that only one study crossed the zero line, indicating a less significant effect. The other thirteen crossed the zero line, indicating an advantage in the experimental group. The diamond model depicts the combined effect size of all studies, which is close to one. The results of the analysis of all studies are presented in Table 2 below.

Table 2. Summary of Data Analysis Results

Model	N	Hedges's g	Standard Error	Test of Null		Heterogeneity	
				Z-value	P-value	Q	P
Fixed-effects	14	0.84	0.007	11.82	0.00	28.9	0.01
Random-effects	14	0.85	0.008	9.76	0.00		

Based on Table 2, the heterogeneity test yielded a Q statistic of 29.9 ($p < 0.05$) and an I^2 statistic of 51%, indicating moderate heterogeneity among the included studies. This variability suggests that differences in study characteristics, such as educational level and software used, likely influence the observed effect size. Further examination of publication bias was conducted by analysing the research funnel plot shown in Figure 3 below.

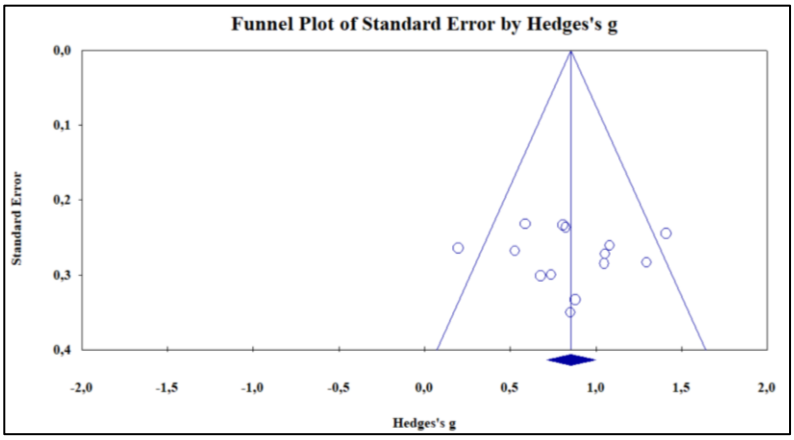


Figure 3. Research Funnel Plot

Publication bias was examined through a visual inspection of the funnel plot (Figure 3), which revealed a nearly symmetrical distribution of studies. This is also evident from the Egger regression test, which yielded a p-value of 0.94 (> 0.05), indicating no publication bias. Therefore, the combined effect size of all studies (0.85) under the random-effects model is considered a large effect size according to Cohen's classification and is reliable for estimating the population.

This study considered educational level and the type of mathematics software as moderators of the study characteristics. Since the heterogeneity test was accepted, further examination of moderator variables associated with the combined effect size across all studies was necessary. Table 3 shows the results of the moderator analysis.

Table 3. Results of the Research Moderator Analysis

Moderator Variables	Category	N	Hedge's g	Heterogeneity		
				(Qb)	df(Q)	P
Educational level	Elementary school	3	1.25	7.46	2	0.02
	Senior High School	7	0.78			
	Senior High School	4	0.72			
Type of software or application	Geogebra	10	0.75	6.39	1	0.01
	Augmented Reality	4	1.19			

Based on the information in Table 3, both study moderators are associated with the overall effect size. In other words, the differences or heterogeneity in the results across the 14 studies are influenced by, among other things, differences in educational level and variations in the mathematics software or applications used.

The findings of this meta-analysis provided strong evidence that Realistic Mathematics Education, when supported by mathematical software, significantly improves students' mathematical abilities (Arifin & Efriani, 2025; Aziz et al., 2025; Lubis et al., 2018; Nguyen, 2023). The moderate to strong overall effect sizes and magnitude suggested that embedding mathematics in meaningful contexts, combined with interactive technology, promotes more profound understanding and engagement (Subaryo et al., 2024; Tamur, Juandi, & Adem, 2020; Tamur, Juandi, et al., 2023; Tamur, Wijaya, et al., 2024; Wangid et al., 2020). Most importantly, these results reinforce the theoretical proposition of RME that learning is most effective when students enjoy and actively solve mathematical problems or mathematise realistic situations with the support of appropriate tools (Juandi et al., 2022; Prahmana & Kusumah, 2020; Zulkardi et al., 2020).

Moderator analysis further clarified the conditions under which software-based Realistic Mathematics Education (RME) is most effective. The more substantial impact observed at the elementary school level (effect size = 1.25) suggests that students at this developmental stage benefit most from *learning by doing* and enjoyable learning experiences within the school environment, where real-life contexts are emphasised and effectively supported by educational technology. The finding that augmented reality (AR) was more influential on the study's effect size (effect size = 1.19) than GeoGebra highlights the power of AR as a bridge connecting students' surroundings with technology (Abdullah et al., 2022; Elmunsyah et al., 2019; Huang et al., 2023; Jiang, 2022; Tamur, Wibisono, et al., 2024). Furthermore, this superior impact also suggests that the visualization, manipulation, and feedback capabilities of the technology used are crucial in supporting the pedagogical goals of RME.

Despite these positive findings, several limitations should be acknowledged. First, the number of high-quality studies combining RME and mathematics software is limited, and most are concentrated in specific regions, which may affect the generalizability of the results. Second, variability in study design, sample size, and measurement instruments may contribute to unexplained heterogeneity. Third, although publication bias tests indicate minimal distortion, the possibility of unpublished null results cannot be ruled out entirely.

These limitations pave the way for future research. Further research is needed at the university level to assess whether software-supported RME can maintain its effectiveness in advanced mathematics learning. Longitudinal studies are also needed to evaluate whether observed improvements persist over time and apply to real-world problem-solving. Furthermore, comparative studies across different software types can help identify specific features that maximise learning outcomes. Ultimately, expanding the research across diverse cultural and educational contexts will strengthen the global relevance of the findings. These results offer important implications for educators, curriculum developers, and policymakers aiming to design effective, technology-based mathematics learning for the 21st Century.

CONCLUSION

This meta-analysis demonstrates that Realistic Mathematics Education (RME) supported by mathematics software has a statistically significant and positive effect on students' mathematical abilities. The overall effect size indicates that integrating RME with digital tools effectively enhances students' mathematical performance. Further moderator analyses revealed that this instructional approach is most effective at the elementary school level, with augmented reality (AR)–based software exhibiting the most substantial impact. These findings highlight the pedagogical value of combining RME with educational technologies to promote deeper conceptual understanding, increased learner engagement, and improved achievement in mathematics education.

Based on these findings, future research should expand the investigation to different levels of education, particularly the tertiary level, and across cultural contexts to strengthen the generalizability of the results. Longitudinal studies are recommended to examine the sustainability of learning gains and their application to real-world problem-solving. A comparative analysis of different types of mathematics software would also help identify the most effective digital tools for supporting RME. For practitioners and policymakers, the integration of RME with software should be prioritised in curriculum design and teacher training to ensure that students benefit from culturally meaningful learning and the convenience of modern technology.

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