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Exploring Integration of Technology in Assessing Mathematics Learning in Early Grades: A Bibliometric Perspective on Research Patterns, Gaps, and Trends

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Abstract

The integration of technology in early childhood education has the potential to transform learning, particularly in early mathematics. However research on its use in assessment remains fragmented, with significant disparities between high-income and low-income regions. This study addresses the gap by analyzing trends, gaps, and patterns in technology-enhanced assessment in early childhood mathematics education. Utilizing a bibliometric approach, data from the Dimensions database (2010–2023) were analyzed using publication trends, citation metrics, and network mapping tools. The findings reveal a significant rise in research post-2020, dominated by contributions from high-income countries such as the United States and Russia, while resource-constrained regions remain underrepresented. Leading authors, including Daphina Bassok and Anna Rorem, and key institutions like the University of Virginia have significantly shaped the field. Influential journals such as *Sustainability* and *Computers and Education* highlight interdisciplinary approaches to bridging the digital divide. Despite progress, notable research gaps persist in addressing equitable access and implementation challenges in low-resource settings. This study provides valuable insights to guide future research, policy, and practical interventions aimed at fostering inclusive, technology-driven assessments that enhance mathematics learning for young learners worldwide.

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Introduction

Globally, early childhood education (ECE) remains a critical yet unevenly accessed stage in the education system, with significant disparities in participation, quality, and resource allocation. Research reveals that nearly 50% of children in low-income countries lack access to pre-primary education, compared to nearly universal enrollment in high-income nations (Earle et al., 2018) These inequities are further compounded by disparities in technological access, which

increasingly shape modern educational practices. For instance, over 75% of teachers in high-income countries have access to digital tools for classroom instruction, while fewer than 25% of their counterparts in low-income regions report similar access (Hennessy et al., 2021). Additionally, only 10-15% of children in low-income countries have access to technology at home, compared to over 60% in wealthier nations (Law et al., 2023). These challenges not only hinder equitable learning opportunities but also jeopardize global commitments such as Sustainable Development Goal (SDG) 4.2, which emphasizes quality early childhood development and education for all children by 2030. Addressing these disparities holistically, including the digital divide, is essential to advancing equity and improving learning outcomes, particularly in foundational areas like early mathematics education (Berson et al., 2022; Verbruggen et al., 2021) mathematical learning opportunities in preschool are limited. Educational technology (ET.

Moreover, Mathematics occupies a central role in early childhood education, serving as a foundation for cognitive development and future success in STEM (Science, Technology, Engineering, and Mathematics) fields. Research highlights the long-term impact of early mathematics instruction on academic achievement, logical reasoning, and problem-solving skills (Watts et al., 2014). Moreover, proficiency in early mathematics is linked to broader educational outcomes, including improved critical thinking and lifelong learning capabilities (Clements & Sarama, 2009). Recognizing its pivotal importance, global education initiatives increasingly prioritize mathematics education during early childhood as a means of fostering equity, sustainability, and economic growth. However, ensuring that all children, regardless of their socio-economic background, have access to quality mathematics instruction remains a significant challenge.

On the other hand, early grades, typically encompassing pre-primary education to grade three, represent a critical phase where foundational academic skills, particularly mathematics, are established (Cutting & Lowrie, 2023; Moore, 2024). Mathematics instruction at this level focuses on fundamental concepts like counting, addition, subtraction, and basic geometry, which are essential for nurturing logical reasoning and problem-solving abilities (Clements & Sarama, 2009). Research highlights that proficiency in early mathematics significantly predicts long-term academic achievement, particularly in STEM fields, and equips learners with vital life skills such as financial literacy (Clements & Sarama, 2016). Given this pivotal role, ensuring that all learners, regardless of their background, receive equitable opportunities to master early mathematics skills is paramount to promoting broader educational equity.

However, recent advancements in technology have transformed early mathematics instruction, offering innovative tools to enhance learning experiences. Digital platforms, including educational apps, virtual manipulatives, and interactive games, provide hands-on opportunities for learners to explore mathematical concepts in engaging and developmentally appropriate ways (Hirsh-Pasek et al., 2015)technology, engineering, and math (STEM. These tools cater to diverse learning styles, bridge abstract mathematical concepts with real-world applications, and promote active exploration of ideas (Akbiyik & Tavil, 2024). As a result, technology-enhanced instruction has become an integral component of contemporary early childhood education practices, helping educators address learning gaps and tailor teaching strategies to individual needs.

Building on the success of technology-enhanced instruction, the integration of technology into assessment practices has opened new possibilities for improving early-grade mathematics education. Tools such as game-based evaluations and adaptive testing platforms offer real-time feedback and personalized learning pathways, enabling teachers to monitor progress and adjust instruction accordingly (Clarke-Midura & Dede, 2010). However, these advancements also present challenges, particularly the need to align assessments with young learners' developmental stages and to address resource disparities in low-income regions (Shute & Rahimi, 2017). This study seeks to systematically analyze how technology-enhanced assessments can be effectively implemented to bridge these gaps and promote equitable learning opportunities in early mathematics education.

In addition to instructional support, technology-enhanced assessment (TEA) offers innovative solutions for evaluating early mathematics learning. TEA tools provide real-time feedback, enabling teachers to monitor progress, adapt teaching strategies, and support diverse learning needs (Redecker et al., 2012). Game-based assessments and computer-adaptive testing have gained traction for their ability to combine engagement with evaluation, offering young learners an interactive and less intimidating alternative to traditional methods (Clarke-Midura & Dede, 2010). Furthermore, TEA aligns with global education trends emphasizing competency-based education and personalized learning pathways, as seen in pioneering countries like Finland, Singapore, and Australia (Çekiç & Bakla, 2021). Despite its potential, however, the adoption of TEA in early mathematics education remains uneven, with significant disparities between high-income and low-income regions.

Thus, these disparities are driven by barriers such as the digital divide, limited access to devices, internet connectivity, and concerns about the developmental appropriateness of digital tools (Plowman et al., 2012; Warschauer & Matuchniak, 2010)discriminating, and eff ective members of society. For others, the ubiquity of these technologies has led to concerns about the ways in which they are seen to exert infl uence on the lives of young children. Like it or not, most people would agree that children's experiences with technology - whether for play, learning, or communication - will have signifi cant implications for their future lives. We prefer to engage with this transformation rather than seek to establish a technology-free version of the past in the present. Nevertheless, we are aware that some of these changes are driven by the marketisation of education (Selwyn, 2011. Additionally, there is a lack of standardized guidelines for integrating TEA into curricula, particularly in resource-constrained settings. The limited research on the long-term impact of TEA and its role in addressing equity further emphasizes the need for a deeper understanding of how these tools can be effectively implemented in diverse educational contexts. Without addressing these barriers, the promise of technology-enhanced solutions to improve learning outcomes in early mathematics education may remain unfulfilled.

While there is a growing body of research on TEA in early mathematics education, systematic analyses of trends, gaps, and research patterns in this field are scarce. This lack of comprehensive analyses limits our understanding of how technology has shaped and continues to influence pedagogical practices and outcomes in early mathematics education. To address this gap, bibliometric studies are essential. They offer unique insights by mapping the evolution of research, identifying key contributors, and highlighting thematic trends (Aria et al., 2023). Such an approach is particularly valuable for understanding how TEA has been studied, the extent to which equity issues have been addressed, and what gaps remain in the literature. By employing a bibliometric perspective, this study seeks to bridge the existing knowledge lacuna, offering a comprehensive analysis of the research field and informing future studies and policies aimed at applying technology to improve early mathematics learning.

Therefore, this study aims to examine trends, patterns, and gaps in the research on technology-enhanced assessment in early mathematics education through a bibliometric lens. Specifically, it seeks to map the development and evolution of technology-enhanced assessment practices, identify foundational contributions, and explore emerging themes. By doing so, the study aligns its objectives with the following guiding questions:

1. What are the publication trends in technology-enhanced assessment in early childhood mathematics education over time?
2. Who are the most influential authors in the field of technology-enhanced assessment in early childhood mathematics education?
3. Which institutions and countries contribute most significantly to the research on technology-enhanced assessment in early childhood mathematics education?
4. Which is the most cited journals on technology-enhanced assessment in early childhood mathematics education?
5. What are the authors' most frequently used keywords the in early childhood mathematics education?

6. What are the most cited publications in the field of technology-enhanced assessment in early childhood mathematics education?

Through addressing these questions, the research seeks to offer a comprehensive understanding of the field, including how digital assessments can address challenges of equity, accessibility, and learning outcomes in diverse contexts. Ultimately, the findings will provide valuable insights for teachers, policymakers, and researchers striving to develop inclusive, effective, and scalable educational technologies for young learners.

Methodology

This study employed a bibliometric approach, utilizing the Dimensions database, (https://www.dimensions.ai) to uncover research gaps, emerging trends, and patterns in technology-enhanced assessment within early childhood mathematics education. With its vast coverage of top-notch peer-reviewed journals, edited books and book chapters, Dimensions database is acknowledged as one of the most complete and trustworthy databases for bibliometric analysis in educational research (García-Sánchez et al., 2019). In order to maintain high standards of publishing quality, the database is updated on a regular basis, assuring that only significant and relevant studies are included. This makes it the perfect resource for capturing how this field of study is developing.

A systematic search was conducted in the Dimensions database on November 15, 2024 using the following search string: ("Technology-enhanced assessment" OR "Digital assessment" OR "Computer-assisted assessment" OR "E-assessment" OR "Online assessment") AND ("Early childhood education" OR "Preschool education" OR "Kindergarten" OR "Early years education" OR "Nursery education" OR "Pre-primary education") AND ("Mathematics education" OR "Math education" OR "Mathematics learning" OR "Math instruction" OR "Mathematics teaching" OR "Numeracy education") AND (LIMIT-TO (LANGUAGE, "English")). This search was restricted to documents published between 2010 and 2023 to align with the growing interest in technology-enhanced educational practices, particularly following significant advancements in educational technology over the last decade (Jing et al., 2024).

Inclusion and exclusion criteria

To guarantee academic rigor, the papers chosen for this study were subjected to precise inclusion and exclusion criteria. Publications from 2010 to 2023 were included to capture recent trends and advancements in technology-enhanced assessment in early childhood mathematics education. The focus on this period ensures that the study reflects contemporary research influenced by technological innovations, such as mobile applications, artificial intelligence, and adaptive learning systems, which have revolutionized assessment practices (Chen et al., 2021). This time frame also aligns with significant shifts in educational policies and global digital transformation initiatives that have shaped teaching and learning practices over the past decade (Balyer & Öz, 2018). Only studies directly addressing technology-enhanced assessment in early childhood mathematics education were considered, and publications were

Table 1: Publication inclusion and exclusion criteria

Criteria	Inclusion criteria	Exclusion
Database	Dimensions database	Other database
Accessibility	Open access	Closed access
Publication period	From 2010-2023	Documents published before 2010 and in 2024
Document type	Articles, edited books and book chapters	Conference proceedings, reports, Monographs, thesis and dissertations
Subject area	Articles, edited books and book chapters focusing on technology-enhanced assessment in early childhood mathematics education	Publications that did not directly address technology-enhanced assessment or early childhood mathematics education
Language	English	Other languages
Text availability	Studies for which the full text is available	Studies for which the full text is not available

restricted to English to maintain consistency and avoid translation inaccuracies (Brunetti et al., 2020)public administrators and organisations in the education industry can undertake to successfully face the challenges of digital transformation in a regional innovation system. This research considers stakeholders that operate in the Tyrol–Veneto macroregion (the Tyrol, South Tyrol and Veneto areas. To ensure validity and reliability, peer-reviewed articles, edited books, and book chapters were included, while grey literature, such as editorials, reports, conference proceedings, and theses, were excluded as they often lack rigorous peer review (Jing et al., 2024). These criteria were designed to ensure the inclusion of high-quality sources that adhere to academic norms and provide reliable findings.

Data collection, processing and analysis

Following the retrieval of relevant documents from the Dimensions database, rigorous data cleaning and preprocessing were conducted to eliminate duplicates and irrelevant entries. Essential metadata for each document, including title, abstract, keywords, authors, publication year, source, citation count, and affiliations, was extracted. This metadata provided the foundation for various bibliometric analyses, including publication trends, citation analysis, and keyword co-occurrence analysis (Aria et al., 2024). To ensure transparency and rigor in the review process, the authors adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to guide the eligibility screening. During this process, inappropriate documents were excluded, resulting in a final dataset of 181 articles for the bibliometric analysis. The screening results are summarized in Figure 1. Such methodologies are integral to ensuring accurate representations of research trends and the impact of scholarly works (Zupic & Čater, 2015).

VOSviewer (version 1.6.20, Netherlands) was used for analysis for this bibliometric study because of its ability to visualize bibliometric networks, including citation networks, co-authorship networks, and keyword co-occurrence networks (Perianes-

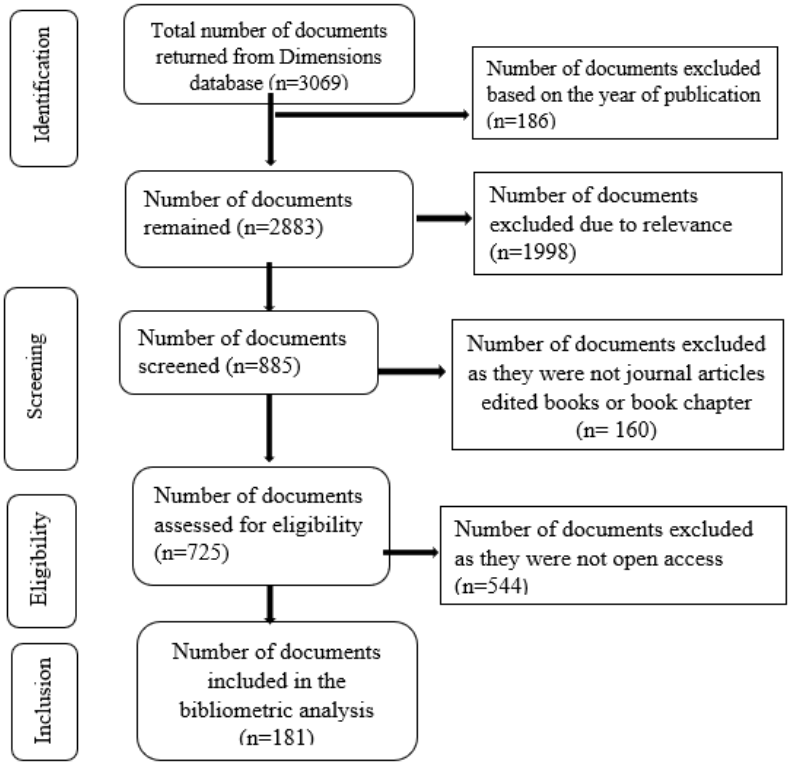

Fig. 1: Flow diagram for the systematic review following the PRISMA statement

Rodriguez et al., 2016; van Eck & Waltman, 2010). A comma-separated values (CSV) file that was exported from the Dimensions database and included funding details, abstracts, keywords, citation data, and other bibliographic information served as the basis for the study (Herzog et al., 2020). This information made it possible to identify collaborative networks, research clusters, and highly influential articles, offering a thorough insight into the development of the topic at hand. Furthermore, bibliometric metrics like publication frequency and citation counts were analyzed to identify noteworthy contributions and long-term patterns (Donthu et al., 2021).

Ethical Considerations

As a bibliometric study, ethical concerns related to human subjects were minimal; therefore, issues regarding participant consent and confidentiality were not applicable. However, by properly citing all sources and using the data in compliance with the guidelines provided by the Dimensions database, ethical research methods were maintained. Furthermore, the research adhered to guidelines for responsible research conduct, ensuring transparency and integrity throughout the analysis process (Zhu & Liu, 2020).

Results

This bibliometric analysis utilized data from the Dimensions database to provide a detailed understanding of research trends and advancements in technology-enhanced assessment within early childhood mathematics education. A total of 3,069 relevant publications, spanning from 2010 to 2023, were identified, representing diverse journals and contributions from researchers across various countries worldwide. The findings reveal the dynamic nature of this field, highlighting key publication trends, influential studies, and emerging areas of inquiry that have shaped the discourse over the past decade. This section is organized into subsections to present the results clearly and concisely, offering interpretations and conclusions drawn from the study.

Annual publication distribution and growth patterns

The yearly increase in publication numbers acts as an important measure of research engagement and interest within a particular field. Analyzing these patterns offers valuable insights into the shifting priorities of the research community and potential areas of future exploration (Kombe, 2023). In the case of technology-enhanced assessment in early childhood

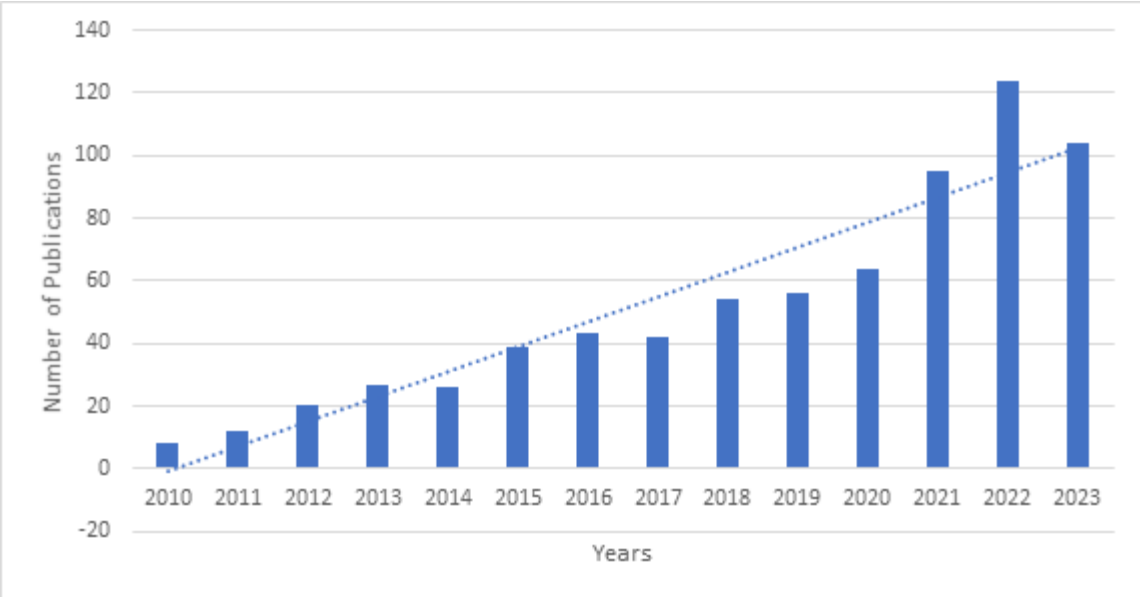

Fig. 2: Annual publication trends on technology-enhanced assessment in early childhood mathematics education

mathematics education, the number of publications per year reflects a rapidly developing field. During the early 2010s, the topic received limited attention. However, a significant surge in interest emerged by 2022, culminating in an unprecedented peak of 124 published documents, reflecting a marked increase in scholarly activity.

Figure 2 depicts a steady increase in scholarly activity since 2010, demonstrating the expanding global recognition of the importance of integrating technology into early mathematics assessment. While the overall trend shows growth, the annual number of publications has exhibited fluctuations, suggesting periods of varying research intensity in the field. Overall, the approximately 155 increases in publications from 2010 to 2023 suggests that the field is still maturing, with significant potential for future growth. This upward trend indicates a shift towards more detailed exploration and increased recognition of the role of technology in enhancing assessment practices for young learners.

The most influential authors

Table 3 ranks the top ten most prolific authors in this field based on their total publications (TP), highlighting the leading contributors to research on this topic. Topping the list is Olivier Jako from the Commonwealth of Learning, who has made significant strides with seven publications, advancing the understanding of technology-enhanced assessment in early childhood mathematics education. Following closely are Lubbe Anitia and Mentz, Elsa both from North-West University, with five and four publications, respectively. Their active engagement in the field reflects their influential role in shaping the research contexts and uncovering emerging trends. This ranking not only acknowledges the authors' contributions but also highlights their impact on the field.

Interestingly, a different perspective emerges when focusing on citations. The most highly cited authors Bassok Daphina, and Rorem Anna, both from the University of Virginia, along with Latham Scott, from Princeton University have each accumulated 388 citations, despite having published only one article. This indicates that their individual publications have had a profound impact, attracting substantial academic attention and significantly contributing to the discourse in this area.

The most influential institutions

Further, the analysis revealed the most influential institutions contributing to the literature on technology-enhanced assessment in early childhood mathematics education. Within the institutional collaboration network, 61 institutions were identified, with 27 meeting the minimum threshold of at least two citations to be included in the network. Among these, the University of Virginia emerged as the leading institution in terms of citations, having accumulated a total of 388 citations. This prominence reflects the

Table 2: Rank order of the 10 most productive authors

Rank	Author	Institute	Country	TP	TC	AC
1.	Olivier Jakdrio	Commonwealth of Learning	United States	7	19	2.7
2.	Lubbe, Anitia	North-West University	United States	5	2	2.5
3.	Mentz, Elsa,	North-West University	United States	4	2	2
4.	De Beer, Josef	University of the Western Cape	South Africa	3	11	3.7
5.	Moll, Ian	University of the Witwatersrand.	South Africa	2	8	4
6.	Du, Toit-Brits, Charlene	North-West University	United States	2	5	2.5
7.	Du, Toit, Adri	North-West University	United states	2	3	0.7
8.	Raitskaya, Lilia K.	Moscow State Institute of International Relations	Russia	2	2	1
9.	Lambovska, Maya	University of National and World Economy	Bulgaria	2	2	1
10.	Wirth, Karl R.	Macalester College	United States	2	2	1

TP-Total Production, TC-Total Citation, AC-Average Citations

university's significant contributions to advancing research in technology-enhanced assessment for early childhood mathematics education.

Following the leading institution are two prominent universities from England: The University of Cambridge, with 36 citations, and Durham University, with 25 citations. Furthermore, four Finnish institutions, the Division of Social and Health Services, the University of Helsinki, the University of Turku, and Abo Academy University each received 12 citations, demonstrating the active participation of Finnish academics in this area. Asia's contribution to the discussion is represented by the University of Science and Technology of China, which also has 12 citations on the list. This wide geographic representation highlights the transnational character of research efforts in this field and the broad awareness and scholarly interest in developing technology-enhanced assessment in early childhood mathematics education.

Moreover, the analysis shows that the Moscow State Institute of International Relations leads the field in terms of publications, with three contributions, while the University of National and World Economy follows with two. This pattern highlights a concentration of research activity in European countries, particularly Russia and Bulgaria. Moreover, institutional collaboration appears limited, as connections are mainly observed among Finnish institutions, as shown in Figure 3. These findings suggest a need to expand international research partnerships to foster a broader exchange of knowledge and drive collaborative progress in technology-enhanced assessment within early childhood mathematics education.

Most influential journals

The co-citation analysis conducted through VOSviewer reveals key journals that shape the scholarly contexts in the integration of technology for assessing mathematics learning in early grades. Out of 940 sources reviewed, 54 met the minimum threshold of 10 citations, identifying a select group of highly influential journals. As shown in Table 7, *Sustainability* stands out as the most cited source, with 73 citations, signifying its prominence in publishing research that intersects digital technology and educational assessment in early grade classes. Following closely is the *Journal of Computers and Education*, with 58 citations, which highlights its significant role in advancing knowledge on technology-enhanced learning, particularly in mathematics education for young learners. The *Journal of Teaching and Teacher Education* occupies the third spot, with 42 citations, further emphasizing the importance of teacher preparation in implementing digital tools for early mathematics assessment.

The top 10 journals together account for 359 citations out of the total 1003, highlighting their centrality in the discourse on integrating digital technology in early mathematics assessment. This prominence indicates a growing recognition of the value of incorporating technology in assessing mathematics learning for young students, aiming to improve educational outcomes. On the other hand, the analysis of link strength, illustrated in Figure 4, shows that *Sustainability* has the highest link strength, with 3,823 connections, indicating extensive cross-references with other sources. The *International Journal of Technology and Design Education* follows, connected 2,157 times, and the *Journal of Distance Education* with 1,670 connections. This pattern of link strength suggests a robust interdisciplinary network, which integrates insights from sustainability, educational technology, and distance learning to enhance mathematics assessment practices for early grades.

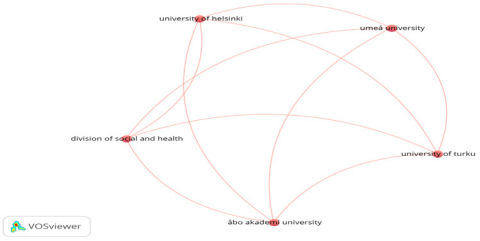

Figure 3: Co-authorship patterns between institutions

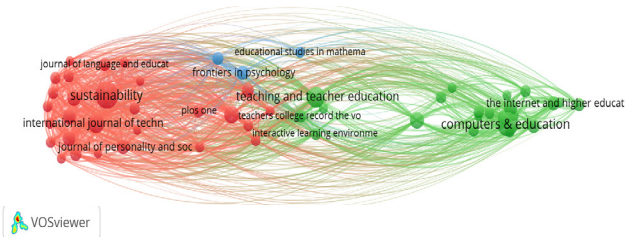

Figure 4: Network visualization of co-citation journals

Most productive countries

The analysis of the most productive countries in integrating technology into mathematics assessment for early grades reveals notable patterns in research output and influence. Using bibliographic coupling with a minimum threshold of 5 citations, 23 out of 50 countries met the criteria. In terms of publications, Russia leads with 6 publications, followed by the United States and United Kingdom with 4 each. Five countries including Tanzania, China, Spain, Finland, and Sweden each contributed 2 publications, as shown in Table 3.

In terms of citations, however, the United States ranks first, with 427 citations, averaging 106.75 citations per document. The United Kingdom follows with 95 citations, and Spain takes third place with 44 citations. A noteworthy aspect of this analysis is Russia's high publication count but low citation impact, with just 7 citations in total, averaging 1.6 citations per document, suggesting a potential gap in the international recognition or applicability of its research. The presence of Tanzania, a Global South country, with 34 citations highlights the emerging contributions from regions historically underrepresented in educational technology research. This demonstrates the expanding global interest in technology-driven educational practices and emphasizes the importance of fostering international collaboration in this field. These results are illustrated in Figure 5, which presents the bibliographic coupling map of country authorship.

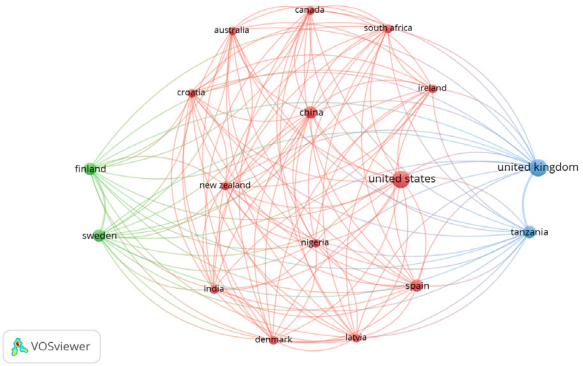

Fig. 5: Network visualization of bibliographic coupling of countries

Co-occurrence of keywords

Author keywords serve as a vital indicator of research trends, capturing the core themes and evolving interests within a field. They play an indispensable role in tracking and evaluating the scientific progress across various domains, as they reflect both established topics and emerging areas of inquiry (Kombe, 2023). Through the strategic use of keyword analysis, researchers can gain an insightful overview of the current research contexts, identify priority areas, and highlight gaps that warrant further investigation (Rejeb et al., 2022).

In this study, VOSviewer was employed to conduct a co-occurrence analysis of author keywords extracted from title and abstract fields where the analysis unit was set to "author keywords" to focus explicitly on topics the researchers deemed essential. Out of 3,185 author-provided keywords, a subset of 71 keywords met the threshold for analysis by appearing more than 20 times, with the 20 most frequently used keywords highlighted in Table 4. This analysis offers a structured look into the most prominent research

Table 3: Most productive countries

Rank	Country	Documents	Citations	Average citations	TLS
1.	Russia	7	7	1.6	1242
2.	United States	4	427	106.75	400
3.	United Kingdom	4	95	23.75	470
4.	Spain	2	44	22	402
5.	Finland	2	40	20	465
6.	Sweden	2	40	20	465
7.	China	2	40	20	400
8.	Tanzania	2	40	20	468

*TLS-Total Link Strength

topics within the scope on integrating technology in mathematics learning assessment for early grades, revealing both the breadth and focus areas that characterize the field.

The analysis reveals that the most frequently used keywords include "self," which appears 305 times, followed by "assessment" (161 times), "teaching" (158 times), "field" (141 times), and "use" (103 times). This frequency suggests a strong research focus on self-assessment practices, evaluation methods, and instructional approaches within the context of integrating technology in educational settings.

The network map presented in Figure 8 illustrates the co-occurrence of author keywords, organized into four distinct clusters with a total of 43 keywords. Each color represents a unique thematic cluster, which reveals different focal areas within the research contexts. Cluster 1 (Green) is the largest, comprising 19 keywords. This cluster predominantly covers themes related to "assessment" and "higher education," suggesting a strong emphasis on evaluative frameworks and academic contexts. The keywords within this cluster exhibit larger node sizes, indicating higher frequency and centrality in the research discussion. Cluster 2 (Blue) contains 10 keywords, including terms such as "field," "theory," and "chapter." This cluster reflects foundational and theoretical aspects of the research area. The presence of both small and large nodes within this cluster suggests a blend of frequently discussed terms alongside emerging or specialized concepts. Cluster 3 (Red) encompasses 9 keywords, featuring keywords like "teaching," "use," and "ICTs." This cluster highlights the practical and applied dimensions of technology integration in educational practices. The prominent node sizes in this cluster emphasize the importance and recurrence of these themes within the literature.

Cluster 4 (Yellow), with 5 keywords, occupies a central position in the network map and includes keywords such as "conference," "proceeding", and "paper". This cluster seems to act as a bridge between other thematic areas, facilitating interdisciplinary connections and discussions. The smaller node sizes in this cluster imply that while these keywords are essential for linkage across topics, they may have less individual prominence.

Table 4: Most used keywords

Rank	Keyword	Occurrences	Relevance
1	Self	305	1.31
2	Assessment	161	0.76
3	Teaching	158	0.64
4	Field	141	0.82
5	Use	103	1.05
6	Researcher	98	0.55
7	Scholarship	79	1.40
8	Higher education	73	0.70
9	Role	69	0.99
10	Mathematics	68	0.99
11	Chapter	66	0.95
12	science	64	0.51
13	Digital technology	63	1.21
14	Society	58	1.18
15	Conference	54	0.85
16	Teacher education	54	1.07
17	Environment	51	0.78
18	Work	50	0.70
19	Volume	50	0.60
20	International conference	49	1.21

Discussion

The integration of technology in assessing mathematics learning in early grades has become an increasingly prominent area of research, driven by the growing recognition of its potential to enhance educational practices and outcomes. This discussion critically examines the study key findings, offering insights

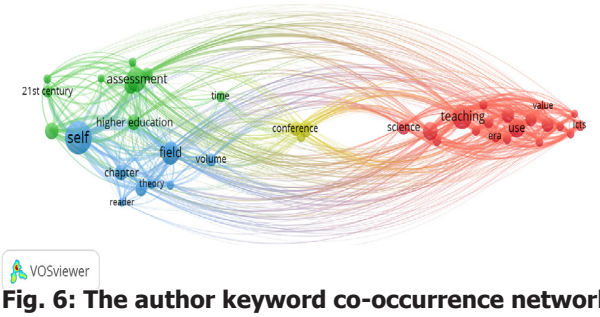

Fig. 6: The author keyword co-occurrence networks

into the patterns, trends, and gaps characterizing this field. By analyzing annual publication growth, influential contributors, and the co-occurrence of keywords, it unravels the complexities shaping this evolving domain. The findings not only highlight the significant progress made but also underline the opportunities and challenges that lie ahead, setting the stage for future research and collaboration in the integration of technology within early childhood mathematics education.

The annual publication distribution and growth patterns in the field of technology-enhanced assessment for early childhood mathematics education reveal a promising path. The steady increase observed since 2010, culminating in a peak of 124 publications in 2022, highlights the growing academic recognition of this area as a vital component of modern educational practices. This trend aligns with the global movement toward integrating technology in education, as noted by Yelland & Gilbert (2018), and reflects similar findings by Starkey (2020), who emphasize the transformative potential of digital tools in enhancing early learning environments. These growth patterns suggest an evolving understanding of technology as not just a supportive tool but a critical driver of innovation in assessment practices. However, the fluctuations in annual publications point to varying research priorities and challenges, as echoed by Sosa Neira, et al., (2018), who highlights funding inconsistencies and contextual barriers in implementing technology across diverse educational settings.Contrasting findings from earlier studies add depth to this analysis. For instance, while Davis et al., (2019) and (Sosa Neira, et al., (2018) observed a slower adoption of technology in assessment, particularly in under-resourced regions, the rapid surge post-2020 suggests a paradigm shift, possibly accelerated by the COVID-19 pandemic. The global crisis forced educational institutions to adopt digital solutions, thereby boosting research interest in technology-enhanced assessments. However, this growth may still lack equity in application, as noted by Starkey (2020) who argues that technological advancements often benefit high-income settings disproportionately. Thus, the overall increase in publications indicates a maturing field with significant potential. Still, it also calls for more context-specific studies to address disparities and ensure the widespread effectiveness of these innovations. Such targeted research could ensure that technological integration in mathematics assessments benefits learners across diverse socioeconomic and cultural contexts.

On the other hand, the analysis of the most influential authors reveals a detailed understanding of scholarly contributions in the field of technology-enhanced assessment for early childhood mathematics education. Olivier Jako from the Commonwealth of Learning leads in terms of total publications, with seven works advancing critical conversations in this domain. Similarly, Lubbe Anitia and Mentz Elsa, both affiliated with North-West University, have contributed five and four publications, respectively, underlining their sustained engagement with the subject. These authors not only expand the body of knowledge but also influence research trajectories by exploring emerging trends and context-specific applications. Their output mirrors broader findings in bibliometric studies, such as those by Ioannidis, (2023) which emphasize that prolific authors often serve as catalysts for shaping research paradigms in nascent fields.

However, citation-based influence offers a compellingly different perspective. Authors like Bassok Daphina and Rorem Anna from the University of Virginia, and Latham Scott from Princeton University, each with only a single publication, have accrued 388 citations. This stark contrast highlights the importance of depth and quality over sheer quantity. Their highly cited works resonate with the findings of Zeng et al., (2022), who argued that impactful research often transcends publication volume, addressing foundational questions or presenting groundbreaking insights. Furthermore, this phenomenon aligns with insights by Leydesdorff & Rafols (2011), who observed that citation metrics can serve as a proxy for the transformational influence of individual studies.

The divergence between publication volume and citation impact also reflects the varied pathways to academic influence. While Jako, Lubbe, and Mentz's multiple contributions build a comprehensive understanding of the field, the singular works of Bassok, Rorem, and Latham have likely sparked new directions in research or policy. This dual dynamic, where both prolific and single-impact authors

contribute meaningfully, emphasizes the field's vibrancy and potential. Future investigations might dig deeper into the thematic focus of these works to uncover how they align with or diverge from broader trends, ultimately enriching the discourse on integrating technology in mathematics assessment for young learners.

However, certain challenges persist. While prolific authors address a broader spectrum of topics, gaps remain in understanding how their contributions specifically influence practice or policy, a limitation noted by Donthu et al. (2021). Conversely, while high-impact studies make significant breakthroughs, their limited number raises questions about their replicability and scalability in diverse educational contexts. These unresolved issues highlight the need for future research to bridge the gap between thematic breadth and impactful depth, ensuring that innovations are both theoretically robust and practically applicable.

On the other hand, The University of Virginia's leading position, with 388 citations, illustrates its significant influence on research related to technology-enhanced assessments in early childhood mathematics education. Its contributions have laid a strong foundation for advancing this domain, reflecting the institution's global relevance and impact. Similarly, the University of Cambridge and Durham University, with 36 and 25 citations respectively, highlight the UK's leadership in integrating educational technology into learning and assessment. This aligns with findings from Marginson (2022) who emphasized the UK's role in driving innovation in global educational practices. The prominence of these institutions underlines their commitment to addressing emerging trends in the field.

Finnish universities, including the University of Helsinki and Abo Academy University, further exemplify regional excellence by collectively accumulating 12 citations. These institutions reflect Finland's renowned focus on early education and technological integration, as noted by Tani et al., (2018). Their contributions illustrate a cohesive approach to employing technology for enhancing learning outcomes in young learners. Similarly, the inclusion of the University of Science and Technology of China signifies Asia's growing scholarly engagement in this area. This geographic diversity highlights the global diffusion of research on technology-enhanced assessments.

Contrasting these citation-driven impacts are institutions such as Moscow State Institute of International Relations and the University of National and World Economy, which led in publication volume but had relatively lower citation impact. This discrepancy highlights the importance of research quality over quantity, aligning with Al-Jamimi et al. (2022)India, Mexico, and Brazil observation that impactful studies often influence the field regardless of publication frequency. Such findings call for a balanced focus on both productivity and high-quality contributions to drive meaningful progress.

The limited institutional collaboration, especially outside Finland, presents an opportunity to strengthen global partnerships in this research domain. International collaboration could enrich the field by incorporating diverse perspectives and addressing unique regional challenges. Engaging underrepresented regions, such as Africa and Latin America, would ensure more inclusive advancements in technology-enhanced assessment. Such efforts could create a more equitable foundation for integrating technology into early mathematics education, benefiting teachers and learners across diverse settings (Hennessy et al., 2022).

Also, the analysis highlights *Sustainability* as the most influential journal, with 73 citations and a link strength of 3,823, signifying its pivotal role in bridging educational assessment and sustainable development. This aligns with Leal Filho et al. (2019), who emphasized the journal's contribution to advancing education-related Sustainable Development Goals (SDGs). Similarly, the *Journal of Computers and Education*, with 58 citations, confirms its leadership in publishing research on digital learning technologies, as observed by Liu (2022). The *Journal of Teaching and Teacher Education* (42 citations) further underlines the critical role of equipping teacher with the competencies needed to effectively implement technology, supporting findings by Darling-Hammond et al. (2020). Together, these journals reflect a clear prioritization of interdisciplinary and practical approaches to enhancing early mathematics assessments.

While the dominance of these journals reflects high-quality research, their focus on global contexts raises concerns about the inclusivity of underrepresented regions. For instance, Verhoeven, (2011)with a view to social justice. It examines how educational systems organize ethno-cultural difference and how this process contributes to inequalities. Theoretical resources are drawn from social philosophy as well as from recent developments in social organisation theory. It is argued that ethnic minority pupils face multiple sources of inequalities, of a social (redistributive argued for greater diversity in research to address unique educational systems and challenges. The strong interdisciplinary networks indicated by link strength, particularly for *Sustainability* and the *International Journal of Technology and Design Education*, suggest opportunities for collaboration across fields. These connections could integrate insights from sustainability, design, and technology to create comprehensive solutions for early mathematics assessment. Encouraging contributions from emerging journals focused on regional studies, as suggested by Chen et al. (2015), could expand the scope of this field and foster a more globally representative knowledge base.

The concentration of 359 citations among the top 10 journals, out of 1,003 total citations, underlines the reliance on a select few sources. This pattern reflects the quality and centrality of these journals but highlights a potential gap in diversifying research perspectives. Broadening the scope by engaging with less-cited journals and promoting interdisciplinary collaborations could enrich the field. Such efforts would not only ensure a more inclusive representation of educational systems but also drive innovative practices in technology-enhanced assessment for early mathematics education.

The analysis of productive countries reveals geographic disparities and evolving trends in technology-enhanced mathematics assessment research. Russia leads in publication output but exhibits limited impact, averaging only 1.6 citations per document. This aligns with (Bornmann & Leydesdorff (2014), who observed that high research output without strong international collaboration often results in low citation impact. By contrast, the United States achieves exceptional citation performance, averaging 106.75 citations per document, reflecting the global relevance and quality of its research, as supported by Kwiek (2021). These findings highlight the importance of both collaboration and research quality in achieving meaningful scholarly influence on a global scale.

The United Kingdom and Spain also demonstrate notable influence, with 95 and 44 citations, respectively, emphasizing their alignment with global priorities like digital innovation in education. Tanzania's emerging presence, marked by 34 citations from two publications, highlights the increasing contributions of Global South countries. This finding resonates with Chen et al. (2015), who emphasize the importance of underrepresented perspectives in diversifying global education research. Tanzania's performance exemplifies the potential of localized studies to address unique challenges while contributing to broader educational discourse.

The bibliographic coupling map reveals limited interconnectivity among countries, particularly between Global North and South nations. Strengthening these collaborations, as proposed by Leal Filho et al. (2019), could enhance the inclusivity and global impact of research on technology in early-grade mathematics assessment. Initiatives such as joint publications and cross-cultural studies could bridge gaps in recognition, foster equitable research partnerships, and enrich the global knowledge base. Encouraging such collaborations would support a more comprehensive understanding of integrating technology into mathematics education across diverse educational contexts.

The co-occurrence analysis of keywords offers critical insights into the status of research on technology-enhanced mathematics assessment for early grades, revealing established priorities and potential gaps. Keywords like "self," "assessment," and "teaching" dominate the discourse, reflecting a concentrated focus on self-regulated learning, evaluative strategies, and instructional approaches. This emphasis indicates that the field is relatively advanced in exploring core concepts of assessment and pedagogy, particularly through digital tools, as suggested by Nicol & MacFarlane-Dick (2006). However,

the absence or low frequency of keywords related to equity, accessibility, and localized educational needs highlights notable research gaps. These gaps suggest that while the field has made significant strides in general frameworks and technological integration, critical issues such as inclusivity, culturally responsive practices, and technology adaptation for marginalized contexts remain underexplored. Addressing these areas could expand the applicability of findings and ensure a more equitable impact across diverse educational settings.

The thematic clusters illustrate a balanced interaction between theoretical foundations and applied practices. Foundational themes align with established frameworks like Mishra & Koehler's (2006) while addressing the complex, multifaceted, and situated nature of this knowledge. We argue, briefly, that thoughtful pedagogical uses of technology require the development of a complex, situated form of knowledge that we call Technological Pedagogical Content Knowledge (TPCK TPACK model, underscoring the theoretical scaffolding that supports practical advancements. However, the recurring emphasis on applied aspects, such as the use of ICTs in instructional contexts, suggests a trend toward aligning research with real-world educational challenges. This interplay highlights both continuity with past studies and a gradual shift toward translational research aimed at addressing classroom-specific issues. The concentration of research in well-defined areas, such as assessment and teaching, contrasts with limited attention to interdisciplinary or emergent themes, pointing to opportunities for further investigation into cross-cutting issues like the integration of artificial intelligence, gamification, and adaptive learning systems in mathematics education.

Conclusion

This study systematically examined the research context on technology-enhanced assessment in early childhood mathematics education, unveiling key trends, influential contributors, and emerging themes. The findings underline the transformative potential of TEA in bridging learning gaps, promoting inclusivity, and enhancing early numeracy outcomes (See et al., 2022). However, significant disparities persist in research outputs, with high-income countries leading in publications and citations, while low-income regions face systemic challenges, such as limited access to digital tools, inadequate infrastructure, and capacity-building deficiencies (Visser et al., 2021;Ghosh et al., 2014)while for the journals we find g=0.65±0.15 for any typical year. We define a new inequality measure, namely the k-index, saying that the cumulative income or citations of (1-k. These disparities reflect broader inequities in global education systems and demand urgent strategies to promote equity, accessibility, and sustainable integration of technology in education.

Moreover, this bibliometric analysis highlighted the contributions of key researchers, such as Olivier Jako, and institutions like the University of Virginia, which have played a pivotal role in shaping the field of TEA. Furthermore, journals such as *Sustainability* and *Journal of Computers and Education* were identified as central to advancing the integration of digital technology and educational assessment. Despite these contributions, the field remains disproportionately influenced by high-income nations, emphasizing the need for more inclusive global research collaborations and initiatives. Empowering low and middle-income countries to contribute meaningfully to this evolving discourse is essential for addressing the global digital divide (Mongeon & Paul-Hus, 2016; Passey et al., 2024) providing a contemporary view of issues, factors and practices that affect education for digitally excluded populations. Concern for how education for digitally excluded populations can be supported is focal to this paper, with different sections offering key related perspectives. From an analysis of issues, factors and practices, actions for policy, practice and research are identified. Given a key finding that power issues can have major effects on plans, implementation processes and outcomes when addressing needs of education for digitally excluded populations, the paper concludes by offering frameworks to support and enable key discussions, to involve representatives from an excluded population as well as those from policy (government and industry.

In addition, key findings also reveal a growing focus on personalized learning and competency-based approaches, facilitated by TEA, which aligns

closely with global educational frameworks, such as Sustainable Development Goal 4.2, advocating for inclusive and equitable education for all children (Prieto-Jiménez et al., 2021). These innovative approaches use digital tools to accommodate diverse learning needs and styles, but significant gaps remain, particularly in integrating equity-focused perspectives and ensuring that TEA tools are developmentally appropriate and culturally responsive (Hirsh-Pasek et al., 2015). Addressing these gaps is critical to making TEA universally applicable and effective in diverse educational contexts. Therefore, this study contributes to the academic discourse by providing a comprehensive overview of the evolution and impact of TEA in early childhood mathematics education. It emphasizes the importance of inclusive research practices and collaborative global efforts to bridge the digital divide and foster equity. Ensuring that TEA benefits all learners, irrespective of their socio-economic backgrounds, is vital for building a more equitable and sustainable educational system. Future research should prioritize culturally sensitive, developmentally appropriate tools and explore strategies to scale up TEA in underserved regions to maximize its transformative potential.

Recommendations

To address the disparities and gaps identified in this study, policymakers and teachers must prioritize the provision of digital tools and internet connectivity in low-income regions. Initiatives such as public-private partnerships and targeted investments are crucial to bridging the digital divide and ensuring equitable access to technology-enhanced learning and assessment. Additionally, fostering international collaborations between high-income and low-income countries can diversify perspectives and promote equitable knowledge production. Research funding bodies should incentivize such partnerships, prioritizing equity and inclusivity in educational technology research.

Future studies should focus on the developmental appropriateness of TEA tools and their effectiveness in addressing challenges faced by marginalized communities, critically exploring how these tools can promote both learning outcomes and social equity. Teacher training programs must be expanded to emphasize the integration of TEA in early mathematics education, equipping teachers with the necessary skills and confidence while ensuring inclusivity for teachers in resource-constrained settings. Furthermore, global education organizations should establish standardized guidelines for implementing TEA across diverse educational contexts, with an emphasis on inclusivity, sustainability, and developmental alignment. Lastly, conducting longitudinal studies is imperative to assess the long-term impact of TEA on learning outcomes, equity, and sustainability, offering critical insights into its role in shaping educational trajectories and societal goals.

Limitation of the Study

One limitation of this study is that it primarily relies on the Dimensions database, which, despite its comprehensive coverage, may not capture all relevant publications, particularly those in languages other than English or grey literature, such as conference proceedings and theses (Visser et al., 2021). This narrow focus could exclude valuable insights from diverse educational contexts and regions with limited English-language research (Hyland & Jiang, 2021). Furthermore, while the study employs rigorous inclusion and exclusion criteria to ensure academic rigor, it may inadvertently overlook studies published in other high-quality databases or those not indexed in Dimensions (Mongeon & Paul-Hus, 2016)namely for research evaluation. Most bibliometric analyses have in common their data sources: Thomson Reuters' Web of Science (WoS. Lastly, the bibliometric approach, while providing valuable insights into trends and influential contributors, cannot fully address the qualitative aspects of TEA, such as its effectiveness in different cultural or socio-economic settings, which are critical for understanding its true impact on early childhood education globally (Jing et al., 2024).

Ethical Issue

Since this is a review study, there is no need for an ethical persission.

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