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Two decades of early grade mathematics (Grade R–2): A systematic and bibliometric review of research trends, challenges, and implications

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Abstract This study presents a comprehensive review of two decades (2005–2025) of research on early grade mathematics (Grade R–2), examining trends, persistent challenges, and implications for teaching, learning, and policy. Using a convergent parallel mixed-methods synthesis design, the study integrates systematic review findings from 17 empirical studies with bibliometric analyses of 42 peer-reviewed articles retrieved from Scopus and Web of Science. Bibliometric results reveal a growing scholarly interest in foundational mathematics post-2015, particularly from South Africa, with dominant research themes including number sense, teacher training, and curriculum design. Systematic review findings highlight persistent difficulties in number sense, mental calculation, spatial reasoning, and word-problem solving. Key contributing factors include limited teacher content knowledge, language-of-instruction mismatches, and inadequate access to manipulatives and professional development. The study is grounded in Ecological Systems Theory, Constructivist Learning Theory, and Human Capital Theory, which collectively underscore the interconnected roles of systemic context, instructional design, and socio-economic outcomes. The review identifies critical gaps in technology-enhanced pedagogy, particularly the integration of AI-assisted tools in early mathematics instruction. It recommends scaling evidence-based practices such as the CPA (Concrete–Pictorial–Abstract) approach, context-relevant teacher training, and aligned language-in-education policies. Findings suggest that addressing foundational mathematics challenges is essential not only for academic equity but also for equipping learners with the cognitive tools needed for lifelong learning and workforce readiness in an increasingly digital economy.

Keywords: foundational numeracy, teacher professional development, curriculum design, language of instruction, number sense, spatial reasoning

1. Introduction

Early grade mathematics (Grade R–2) forms the cornerstone of foundational learning and cognitive development in children, shaping not only their future academic success but also their long-term participation in the workforce (Duncan et al., 2007; Clements & Sarama, 2011). Proficiency in early numeracy is closely associated with better performance in later mathematics, science, and problem-solving domains, which are essential for success in the 21st-century economy (OECD, 2019). Despite the widely acknowledged importance of foundational mathematics, persistent challenges remain across many global education systems, particularly in low- and middle-income countries, where millions of children fail to acquire basic numeracy skills in the early grades (Mosia et al., 2025a, 2025b; Okafor et al., 2023a, 2023b; Okeke et al., 2025; UNESCO, 2023).

In Sub-Saharan Africa, for instance, more than 80% of Grade 2 students cannot perform simple two-digit subtraction, and many struggle to recognize numbers or complete basic sequencing tasks (World Bank, 2022). These gaps are symptomatic of deeper structural and pedagogical issues such as underqualified teachers, curriculum overload, lack of instructional materials, and language-of-instruction mismatches (Piper et al., 2014; Spaull & Taylor, 2015). Foundational learning setbacks at this stage significantly impede learners' future academic progression and reduce their ability to acquire technical and transferable skills needed for employability and innovation (UNICEF, 2022).

Globally, the discourse around foundational learning is gaining renewed momentum, with Sustainable Development Goal 4 (SDG 4) calling for inclusive, equitable, and quality education that ensures all learners acquire basic literacy and numeracy by 2030 (United Nations, 2015). This has placed pressure on governments, educators, and curriculum planners to re-evaluate how early mathematics education is conceptualized, delivered, and supported, especially in relation to national skills planning and workforce development strategies (Anderson & Lin, 2020; Egara & Mosia, 2025; Mosia & Egara, 2025).

Over the past two decades (2005–2025), research on early grade mathematics has expanded substantially, reflecting diverse methodological approaches, thematic foci, and geographical contexts. Yet, there remains a lack of consolidated knowledge on which aspects of early grade mathematics learners struggle with most, why these challenges persist, and how

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they relate to broader goals of skills planning and educational reform. Additionally, little is known about the structure of the knowledge base itself, who is producing this research, which themes dominate, and how scholarly attention has evolved over time.

To address these gaps in the literature, this study conducts a combined systematic and bibliometric review of research published between 2005 and 2025 on early grade mathematics (Grade R–2). The aim is to understand both the structure of the scholarly landscape and the thematic content of the research as it relates to curriculum challenges and implications for skills planning. Specifically, the study is guided by the following research questions:

1. How has scholarly attention to early grade mathematics (Grade R–2) evolved between 2005 and 2025?
2. Which countries, institutions, and authors have contributed most to the research on early grade mathematics during this period?
3. What are the dominant research themes, intellectual linkages and thematic clusters in early grade mathematics literature as revealed through co-occurrence and co-citation analysis?
4. Which specific domains of the early grade mathematics curriculum (Grade R–2) present the greatest learning challenges for learners?
5. What are the key underlying factors contributing to difficulties in early mathematics learning across various educational contexts?
6. What are the implications of early grade mathematics challenges for long-term skills development and workforce planning?
7. How have curriculum design, teacher training, and educational policies addressed these challenges over the past two decades?

1.1. Theoretical framework

This study was anchored in three complementary theoretical perspectives that collectively supported the interpretation of both the systematic and bibliometric review findings: Ecological Systems Theory, Constructivist Learning Theory, and Human Capital Theory. These frameworks provided educational, developmental, and socio-economic lenses for understanding the complex challenges facing early grade mathematics (Grade R–2) and their implications for long-term skills planning.

Ecological Systems Theory, originally proposed by Urie Bronfenbrenner in 1979, emphasized the dynamic interaction between individuals and multiple layers of their environment, from immediate settings like the classroom (microsystem) to broader socio-political contexts such as educational policies (macrosystem). This theory offered a comprehensive framework for understanding how systemic and contextual variables, such as under-resourced schools, teacher quality, curriculum implementation, language policy, and family background, interacted to shape early mathematics learning. Within the present study, Bronfenbrenner’s theory was used to interpret the multi-level nature of the challenges identified in the literature, particularly how environmental conditions across countries and systems contributed to learners' difficulties in mastering foundational mathematical concepts.

To further interpret learner-level challenges and instructional issues, the study also drew upon Constructivist Learning Theory, grounded in the works of Jean Piaget (1952) and Lev Vygotsky (1978). Piaget’s theory of cognitive development highlighted how young children construct knowledge through active exploration, gradually progressing from concrete to abstract thinking. Vygotsky complemented this view by emphasizing the importance of social interaction and the Zone of Proximal Development (ZPD), which refers to the range of tasks a child can accomplish with guidance but not yet independently. Applied to the current study, this theoretical lens helped explain why learners often struggled with certain areas of the early grade mathematics curriculum, particularly when instruction was not aligned with their developmental readiness or lacked appropriate scaffolding. It also informed interpretations of pedagogical mismatches, the need for differentiated instruction, and the importance of culturally responsive teaching approaches in the foundational years.

Finally, Human Capital Theory, developed by Gary Becker in 1964 and refined in 1993, was employed to frame the broader implications of early mathematics learning for national development and workforce planning. This theory conceptualized education as an investment in individuals' future productivity and economic potential. Within the context of this review, Human Capital Theory provided the rationale for linking foundational learning outcomes to skills pipeline development. The reviewed literature revealed that deficiencies in early numeracy not only hindered learners’ future academic achievement but also contributed to long-term disparities in employability, economic participation, and national competitiveness. Thus, this theory helped bridge the micro-level classroom findings with macro-level policy and economic considerations, emphasizing the strategic value of investing in early grade mathematics education.

Together, these theoretical frameworks enabled a holistic interpretation of the literature reviewed in this study. Ecological Systems Theory illuminated the structural and contextual barriers that shape early learning; Constructivist Learning Theory provided insight into developmental and instructional factors; and Human Capital Theory connected educational outcomes with broader societal and economic goals. Their integration aligned with the study’s aim of identifying challenges in early grade mathematics and understanding their implications for skills planning across diverse educational systems.

2. Materials and Methods

This study adopted a convergent parallel mixed-method research synthesis design to explore the challenges in early grade mathematics (Grade R–2) and their implications for skills planning through both a systematic literature review and a bibliometric analysis. This design was appropriate because it allowed for the concurrent but independent collection and analysis of qualitative and quantitative data, which were subsequently integrated to enhance the robustness and depth of interpretation (Hong et al., 2017; Sandelowski et al., 2006).

2.1. Literature search and data sources

Two multidisciplinary academic databases—Scopus and Web of Science (WoS)—were selected for the literature search because of their comprehensive coverage and compatibility with bibliometric tools (Donthu et al., 2021). The search was conducted in July 2025 and limited to peer-reviewed journal articles published between 2005 and 2025. Only studies written in English were included. The search strategy targeted literature on early-grade mathematics education, associated learning challenges, and implications for educational planning and skills development. Boolean expressions were iteratively refined to capture variations in terminology across different educational contexts. The search strategy for each database is summarised in Table 1, which lists the Boolean expressions, time frames, and number of records retrieved before screening. Duplicate records were later removed using RStudio with the bibliometrix package, leaving 42 unique documents for bibliometric and systematic analysis.

Table 1 Summary of database search strategies and results.

Database	Search Period	Search String	Records Retrieved
Scopus	2005–2025	TITLE-ABS-KEY("Grade R" OR "Grade 1" OR "Grade 2" OR "early grade" OR "foundation phase" OR "primary school" OR "early years" OR "elementary school") AND TITLE-ABS-KEY("mathematics education" OR "math education" OR "mathematics teaching" OR "mathematics learning" OR "teaching mathematics" OR "math instruction") AND TITLE-ABS-KEY("challenges" OR "difficulties" OR "barriers" OR "struggles" OR "learning obstacles" OR "learning difficulties" OR "math anxiety" OR "cognitive challenges" OR "conceptual challenges") AND TITLE-ABS-KEY("topics" OR "concepts" OR "skills" OR "understanding" OR "knowledge" OR "number concepts" OR "mathematical concepts") AND TITLE-ABS-KEY("learners" OR "students" OR "pupils" OR "children") AND TITLE-ABS-KEY("South Africa" OR "Malawi" OR "Zambia" OR "Africa" OR "international" OR "cross-cultural" OR "global")	42
Web of Science	2005–2025	TS=("Grade R" OR "Grade 1" OR "Grade 2" OR "early grade" OR "foundation phase" OR "primary school" OR "early years" OR "elementary school") AND TS=("mathematics education" OR "math education" OR "mathematics teaching" OR "mathematics learning" OR "teaching mathematics" OR "math instruction") AND TS=("challenges" OR "difficulties" OR "barriers" OR "struggles" OR "learning obstacles" OR "learning difficulties" OR "math anxiety" OR "cognitive challenges" OR "conceptual challenges") AND TS=("topics" OR "concepts" OR "skills" OR "understanding" OR "knowledge" OR "number concepts" OR "mathematical concepts") AND TS=("learners" OR "students" OR "pupils" OR "children") AND TS=("South Africa" OR "Malawi" OR "Zambia" OR "Africa" OR "international" OR "cross-cultural" OR "global")	12

Note: The combined search across Scopus and Web of Science yielded 54 records (42 from Scopus and 12 from Web of Science). After removing 12 duplicates, a total of 42 unique documents were included for bibliometric analysis.

2.2. Inclusion and exclusion criteria

To ensure the relevance, quality, and focus of the review, clear inclusion and exclusion criteria were applied during the screening process. Only peer-reviewed journal articles published between 2005 and 2025 were considered eligible for inclusion. Studies had to specifically address early grade mathematics (Grade R–2) and engage with instructional, learning, or curriculum-related challenges. Furthermore, eligible studies were required to offer implications for skills planning, teacher preparation, or curriculum development. Only publications written in English were reviewed. In contrast, conference proceedings, editorials, theses, book chapters, and other forms of gray literature were excluded. Articles that focused on upper grades, general STEM education without specific reference to early mathematics, or those that presented tools without discussing educational challenges, were also excluded. Additionally, studies that lacked policy or instructional implications, or were published in languages other than English, were not considered for inclusion.

2.3. Bibliometric analysis

The bibliometric strand of the study was conducted using RStudio (version 2024.12.1) with the Bibliometrix R package (version 4.2.1), via its Biblioshiny interface (Aria & Cuccurullo, 2017). This allowed for the analysis of publication trends, co-authorship networks, citation patterns, institutional productivity, and thematic keyword evolution. Additional visualization and clustering were performed using VOSviewer (version 1.6.20), which generated maps of co-occurrence and intellectual structure, including research hotspots and author collaboration clusters.

2.4. Systematic review and thematic synthesis

The systematic review followed PRISMA 2020 procedures across identification, screening, eligibility, and inclusion. After deduplication, full texts meeting the inclusion criteria (2005–2025; English; Grade R–2 mathematics; instructional/learning challenges with implications for practice or policy) were coded using a structured extraction sheet aligned to the research questions. For each study we captured authorship, country or context, methodological approach, focal curriculum domain(s), contributing factors, principal findings, and implications for skills planning. The qualitative synthesis proceeded via iterative coding and constant comparison, with attention to convergences and divergences across settings and methods. Themes were developed inductively and subsequently mapped to the a priori domains (e.g., number sense, mental calculation, spatial reasoning, problem-solving, language of instruction), ensuring transparency from evidence to interpretation. The screening and selection process is summarised in Figure 1. The characteristics of the included studies are summarised in Table 2.

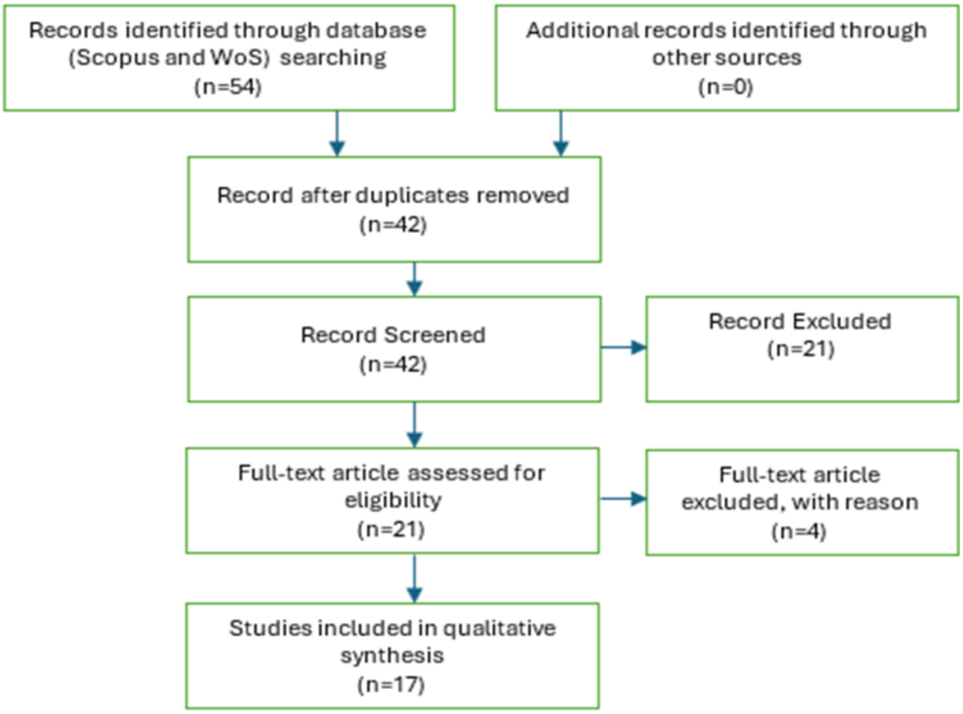

Figure 1 PRISMA 2020 Flow Diagram illustrating article identification, screening, eligibility, and inclusion process.

Following selection, the eligible studies were reviewed in full, and key data such as authorship, country of focus, methodological approach, major findings, and policy or pedagogical implications were extracted. These are summarized in Table 2, which provides an overview of the characteristics of the studies included in the final synthesis.

2.5. Data integration and interpretation

Following separate analyses of the bibliometric and systematic review strands, findings were integrated to provide a holistic understanding of the research landscape. Study-level characteristics and contexts are summarised in Table 2. The bibliometric data highlighted macro-level trends (e.g., publication growth, dominant keywords, geographic concentration), whereas the systematic review illuminated learner-level challenges, pedagogical barriers, and policy gaps across contexts. Integration was achieved through side-by-side comparison, examining convergences and divergences between thematic frequencies (e.g., “number sense,” “teacher training,” “language of instruction”) and the qualitative evidence extracted from the included studies. This approach confirmed alignment between frequently occurring bibliometric themes and the most reported difficulties in the literature (number sense, mental calculation, spatial reasoning, and word-problem solving), as well as the underlying contributors (teacher content knowledge, language mismatches, and resource constraints). The study-level descriptors reported in Table 2 informed this mapping and interpretation. Together, these integrated insights underpinned the targeted implications for curriculum design, teacher preparation, and national skills planning that are advanced in Section 3 (Results and Discussion).

Table 2 Summary of included studies.

Author (s) & Year	Country	Focus Area	Methodology	Curriculum Domain(s)	Contributing Factors	Key Findings	Implications for Skills Planning	Recommendations
Cekiso et al. (2019)	South Africa (Eastern Cape)	Teaching in mother tongue in Foundation Phase	Qualitative interviews with teachers	Language-of-instruction in maths	Multilingual policy, teacher language proficiency	Teachers perceive mother-tongue instruction as beneficial but face linguistic challenges in isiXhosa medium classrooms	Mother-tongue planning can support early numeracy skills	Provide language-specific teacher training, resources in local languages
Hazell et al. (2019)	South Africa (province-wide)	Grade R maths intervention (“R-Maths”)	Quasi-experimental impact evaluation	Early literacy & numeracy in Grade R	Structured intervention, district support, teacher coaching	Intervention led to significant gains in early maths proficiency	Scaling early numeracy interventions yields measurable returns	Integrate R-Maths within provincial policy, ongoing monitoring and teacher support
Maboya et al. (2020)	South Africa	Teachers’ beliefs & use of manipulatives	Survey & interviews with teachers	Mathematics pedagogy	Teacher math knowledge, pedagogical beliefs	Manipulatives help resolve concept-symbol schism; belief influences practice.	Training on symbol-concept connections improves mathematical reasoning	Embed manipulatives and belief-oriented PD in teacher education
Olawale et al. (2024)	South Africa	Bilingual teaching strategies in Foundation Phase maths teacher preparation	Qualitative study with teacher educators	Language-mediated pedagogy	Translanguaging, mother tongue use strategies	Educator strategies foster multilingual competencies and maths content bridging.	Language planning is critical in teacher prep for diverse classrooms	Advocate systematic translanguaging pedagogies and multilingual teacher training
Nakawa et al. (2020)	Zambia	Children’s number sense and composition (pattern/grouping by 10)	Interviews and pilot studies with Grades 1–4 learners	Number sense, subitising & composition	Use of concrete materials, structure-recognition tasks	Recognizing groups of 10 improved calculation ability beyond counting.	Prioritize structural number sense in early curriculum design	Use pattern-based teaching, manipulatives, scaffolded learning tasks
Naroth & Luneta (2015)	South Africa	Implementing Singapore maths curriculum in	Interviews & focus groups with six teachers	CPA (Concrete–Pictorial–Abstract)	CPA approach, manipulatives,	CPA and manipulatives supported	Introduce mastery-based, CPA structured	Provide training on CPA and manipulatives for

		Foundation Phase		maths pedagogy	masterylearning orientation	spatial sense and deeper understanding across ability levels.	instruction in early grades	Foundation Phase teachers
Chitera & Loakes (2012)	Malawi	Language policy conflicts in math teacher training	Qualitative case study of teacher educators	Language-in-education policy & teacher prep	Conflicting language policies, educator beliefs	Mismatched policies hinder teacher confidence to use local languages in maths.	Align language-in-education policy with teacher practice planning	Recommend clear, consistent policy and institutional support for local languages
Bufasi et al. (2024)	Ireland, Latvia, Sweden, Netherlands	Spatial teaching in primary maths & science	Narrative review	Spatial ability across subjects	Curriculum design, teacher training, classroom practice	Identified barriers/enablers in curriculum, pedagogy, PCK, classroom environment for embedding spatial skills.	Spatial ability should be embedded in STEM curriculum planning	Strengthen PD, spatial pedagogies, contextual assessments
Prendergast et al. (2019)	Ireland	Use of children's literature to teach math	Qualitative interviews & surveys	Mathematics instruction, literacy integration	Teacher attitudes, beliefs, training	Teachers see benefits for literacy-numeracy integration but report lack of confidence /resources	Curriculum planning should allow integration of story-based math activities	Include children's literature in teacher education and resource kits
Schuchart et al. (2015)	Netherlands	Role of everyday knowledge, social origin in solving math word problems	Quantitative analysis of performance across social classes	Word problem solving (math)	Socioeconomic status (SES), familiarity with context	Working-class students struggled more when everyday context was unfamiliar.	Planning needs to account for cultural relevance in tasks	Use varied contexts, scaffold unfamiliar scenarios
Sekao & Engelbrecht (2022)	South Africa	Primary teachers' experiences with Lesson Study as PD	Mixed methods—survey + interviews	Teaching methodology; pedagogy	Collaborative reflection, resource constraints, lesson design	Teachers gained pedagogical insights but faced practical barriers.	Lesson Study can inform national CPD strategies	Support teacher clusters, resource improvisation, school leadership endorsement

Vale & Westaway (2024)	South Africa	Pre-service teachers' skills in teaching mental calculation	Work-integrated learning using Mental Starters Assessment Project (MSAP) materials	Mental mathematics, number sense	MSAP materials, structured bridging strategies	PSTs developed competence using bridging strategies for fluency.	Prepare PSTs with structured mental strategy curricula	Scale MSAP, integrate into teacher education
Setoromo & Hadebe-Ndlovu (2020)	Lesotho, South Africa	Teachers' mathematical knowledge in Grade R	Qualitative case study (interviews + observations)	Early numeracy in Grade R	Teacher subject knowledge, policy clarity	Many lacked Shulman's domains of teacher knowledge needed for effective math instruction	Investment in teacher professional knowledge is essential	Strengthen content and pedagogical training, mentoring support
Suseelan et al. (2022)	Global (multi-continental)	Trends and scope of elementary mathematics problem-solving research (1969–2021)	Bibliometric analysis (Scopus data)	Problem-solving research domain	Publication volume, geographic distribution	Increasing global output, uneven geographic representation.	Identify under-researched regions/topics for capacity building	Encourage cross-region collaboration, diversify research topics
Hill & Dowker (2016)	UK / international studies	Early identification of math learning difficulties	Literature review and teacher-rating scale validation	Early numeracy, identification & intervention	Teacher judgment, screening instruments, professional development	Teacher ratings moderately correlated (r ≈ 0.6) with test-based identification.	Early screening needs teacher training and valid instruments in curriculum planning	Integrate rating scales into teacher prep, regular in-class screening
Yang et al. (2021)	Taiwan	Integration of children's literature into mathematics instruction	Survey of 287 in-service and pre-service teachers using Theory of Planned Behavior framework; thematic analysis of open-ended responses	Literacy–mathematics integration	Time constraints, pedagogical knowledge, resources, social norms, attitudes	Identified 11 barriers (e.g. lack of confidence, resources, time) and 11 enablers (e.g. perceived pedagogical benefits, love of literature, enabling norms)	Literature integration as curriculum reform requires awareness, materials, normative support	Provide Continuing Professional Development (CPD) workshops, resource databases, school-level leadership support
Jojo (2023)	South Africa (Eastern Cape)	Classroom innovation during COVID-19	Qualitative interviews with 3 teachers	Intermediate/senior phase mathematics	Use of WhatsApp-based teacher	Teachers adapted instructional	District-level digital peer networks can drive	Support teacher networks (e.g. WhatsApp), promote tech-enabled peer

	teaching practices	collaboration, online tools accessible to learners during lockdown	strategies based on WhatsApp exchanges & online tools, fostering peer learning and innovation	rapid pedagogical innovation in crisis contexts	collaboration, formalize sharing communities

3. Results and Discussion

The integrated findings from the bibliometric and systematic review are presented and interpreted in accordance with the study's convergent parallel mixed-methods design. Guided by Ecological Systems Theory (Bronfenbrenner, 1979), Constructivist Learning Theory (Piaget, 1952; Vygotsky, 1978), and Human Capital Theory (Becker, 1993), the analysis highlights key trends, thematic patterns, and persistent pedagogical challenges in early grade mathematics (Grade R–2) research from 2005 to 2025. The results collectively illuminate both structural shifts in the research landscape and contextual insights into teaching, learning, and policy implications for foundational numeracy and skills development.

3.1. Evolution of scholarly attention to early grade mathematics (2005–2025)

Figure 2 shows the annual scientific production on early grade mathematics from 2005 to 2025, illustrating how scholarly attention to the topic has gradually increased and evolved over time. The earliest publication recorded in this dataset occurred in 2006, with five articles published. However, the period between 2007 and 2011 saw very limited activity, suggesting a lack of sustained research interest or limited visibility of the field during these years. From 2012 onward, there was a resurgence in interest, marked by intermittent but increasing publication rates. A significant turning point occurred in 2020, where the number of publications surged dramatically, indicating heightened interest, possibly influenced by global education disruptions during the COVID-19 pandemic and a renewed focus on early learning recovery. However, this surge was followed by a noticeable decline in 2021, reflecting either a temporary research spike or shifting research priorities. From 2022 to 2024, the trend stabilizes at a relatively higher level than in the early years, though still below the 2020 peak. This post-2020 pattern suggests a sustained, though less intense, scholarly engagement with early grade mathematics. The overall trajectory underscores increasing recognition of foundational numeracy as critical to long-term educational success, especially in the context of equity and recovery in early childhood learning.

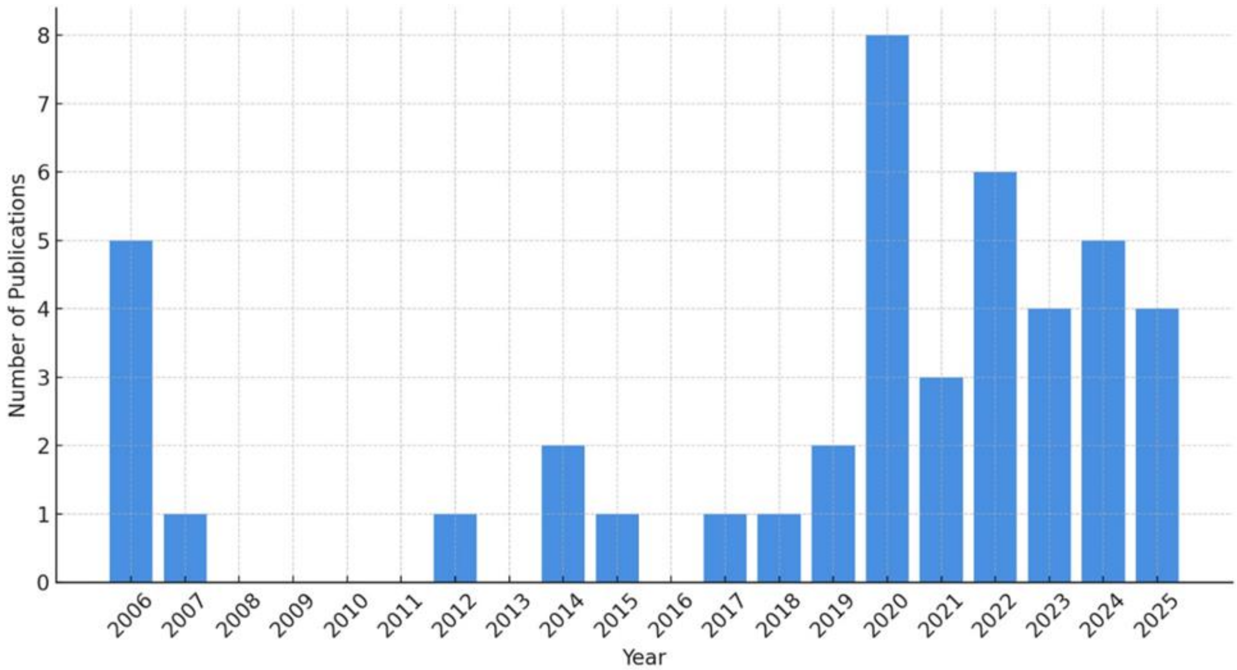

Figure 2 Annual Scientific Production on Early Grade Mathematics (2005–2025).
Source: Scopus and Web of Science databases, visualized using Biblioshiny (Bibliometrix R package).

This upward trajectory aligns with global educational priorities that positioned foundational numeracy as a cornerstone of equitable learning under Sustainable Development Goal 4 (United Nations, 2015). The trend also reflects Bronfenbrenner's (1979) Ecological Systems Theory, which explains how macro-level policy commitments and micro-level classroom practices interact to drive research interest and intervention efforts. The notable surge after 2015 suggests increased policy emphasis on early learning recovery and renewed scholarly focus on the ecological interplay between global reforms and local classroom realities.

3.2. Contributions to early grade mathematics research by country, institution, and author

3.2.1. Contributions to early grade mathematics research by country

Figure 3 illustrates the distribution of contributions across various countries. South Africa stands out as the dominant contributor, with a significant 12 recorded contributions, far surpassing other countries in the field. Ireland follows with 7 contributions, while China, the United Kingdom, and the United States each recorded 3 contributions. This data underscores South Africa's prominent role in advancing research on early grade mathematics, potentially driven by national educational reforms and a concerted focus on enhancing early mathematics education. In contrast, the relatively modest contributions from other countries, such as China and the United States, may suggest that early grade mathematics remains an emerging or specialized area of focus in certain regions, with less widespread academic attention compared to other educational fields. These findings, as illustrated in Figure 3, highlight the geographical concentration of early grade mathematics research, with South Africa leading the charge and other countries contributing at a lower but notable level.

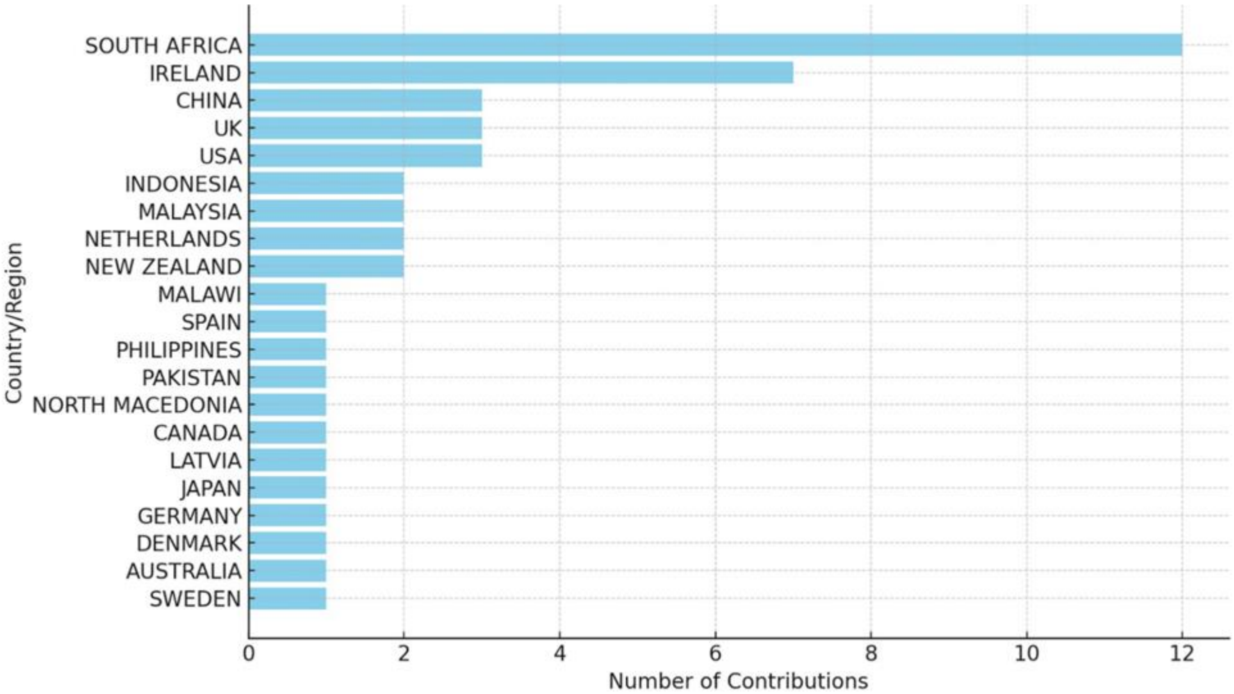

Figure 3 Contributions to Early Grade Mathematics Research by Country.
Source: Scopus and Web of Science databases, visualized using Biblioshiny (Bibliometrix R package).

The dominance of South Africa in publication output reinforces the country's strategic prioritization of foundational numeracy through initiatives aligned with national education reforms. However, the limited representation from other Sub-Saharan contexts underscores an ecological imbalance in research visibility (Bronfenbrenner, 1979). Such regional gaps call for cross-institutional collaboration and capacity-building to diversify the knowledge base. Moreover, the surge in collaboration among European and Asian institutions—evident in co-authorship networks—illustrates Constructivist principles of shared meaning-making and professional learning communities (Piaget, 1952; Vygotsky, 1978).

3.2.2. Institutional contributions to early grade mathematics research

Table 3 shows that the Center for Future Education, Shanghai Jiao Tong University, and the Department of Educational Technology, Shanghai Normal University (China) have the highest Total Link Strength, making them central players in early grade mathematics research. They lead in collaboration, strengthening ties with other institutions. Institutions ranked third, such as Tshwane University of Technology (South Africa), SS Cyril and Methodius University (North Macedonia), and Universitas PGRI Yogyakarta (Indonesia), also play a significant role with a Total Link Strength of 2. Those with a Total Link Strength of 1, including Department of Basic Education, Pretoria and Aalborg University, support the network but are less central. Despite this, their contributions are crucial to the diversity of research in the field.

Table 3 Top 10 institutions based on co-authorship contribution.

Rank	Institution	Cluster	Total Link Strength	Number of Documents
1	Center for Future Education, School of Education, Shanghai Jiao Tong University, China	1	3	1
2	Department of Educational Technology, Shanghai Normal University, China	1	3	1
3	Department of Applied Languages, Tshwane University of Technology, Pretoria, South Africa	8	2	1
4	Institute of Mathematics, Faculty of Natural Sciences and Mathematics, SS Cyril and Methodius University, North Macedonia	6	2	1
5	Accounting Department, Universitas PGRI Yogyakarta, Yogyakarta, Indonesia	3	2	1
6	Aalborg University, Copenhagen, Denmark	2	2	1
7	Department of Basic Education, Pretoria, South Africa	9	1	1
8	Bergische Universität Wuppertal, Germany	11	0	1
9	Kanto Gakuin University, Kanazawa, Yokohama, Japan	15	0	1
10	University of the Witwatersrand, Johannesburg, South Africa	21	0	1

3.2.3. Author contributions and co-authorship in early grade mathematics research

The data on author contributions and co-authorship provides a comprehensive view of the key figures in early grade mathematics research. From Table 4, it is evident that authors such as Benedicic, Ursa, Bowe, Brian, and Buckley, Jeffrey have made significant contributions to the field, as evidenced by their Total Link Strength and the number of documents they have co-authored. These authors have demonstrated strong collaboration patterns, often working with other prominent researchers in the field. The co-authorship network in Figure 4 further supports this, with these authors occupying central positions in the network. The visual representation highlights their influential roles, suggesting they are key players in the collaborative dynamics of early grade mathematics research. The presence of these authors in multiple collaboration clusters indicates their broad impact across various aspects of the field.

Table 4 Top 10 authors based on contribution.

Rank	Author	Cluster	Total Link Strength	Number of Documents	Number of Citations
1	Benedicic, Ursa	1	14	28	2
2	Bowe, Brian	1	14	28	2
3	Buckley, Jeffrey	1	14	28	2
4	Bufasi, Ergi	1	14	28	2
5	Dudareva, Inese	1	14	28	2
6	Duffy, Gavin	1	14	28	2
7	Trakulphadetrak, Natthapoj	2	7	14	4
8	Chen, Chia Huang	2	4	8	2
9	Harbison, Lorraine	2	3	6	2
10	Miller, Sue	2	3	6	2

These collaboration clusters reflect a global epistemic community engaged in continuous reflection on teaching practices and curriculum design—hallmarks of Constructivist pedagogy. Yet, the absence of strong African collaborative linkages indicates under-developed scholarly ecosystems that could be strengthened through south-south partnerships.

3.3. Dominant research themes, intellectual linkages, and thematic clusters

3.3.1. Dominant themes and thematic clusters in early grade mathematics research

Table 5 shows that Mathematics Education and Mathematics are central themes in early grade mathematics research, focusing on teaching and learning foundations. Teaching, Collaboration, and Innovation also emerge as key themes, emphasizing the role of teamwork, new methods, and technologies in enhancing education. Grade R is closely linked to curriculum development for young learners, while Barriers like word problems and spatial ability highlight challenges faced by both students and teachers. Cluster 1 emphasizes these challenges, while Clusters 2 and 3 focus on proactive solutions such as

Curriculum, Lesson Study, and Collaboration, which aim to improve teaching strategies. Figure 5 visually supports these findings by illustrating the connections between these themes in the co-occurrence map.

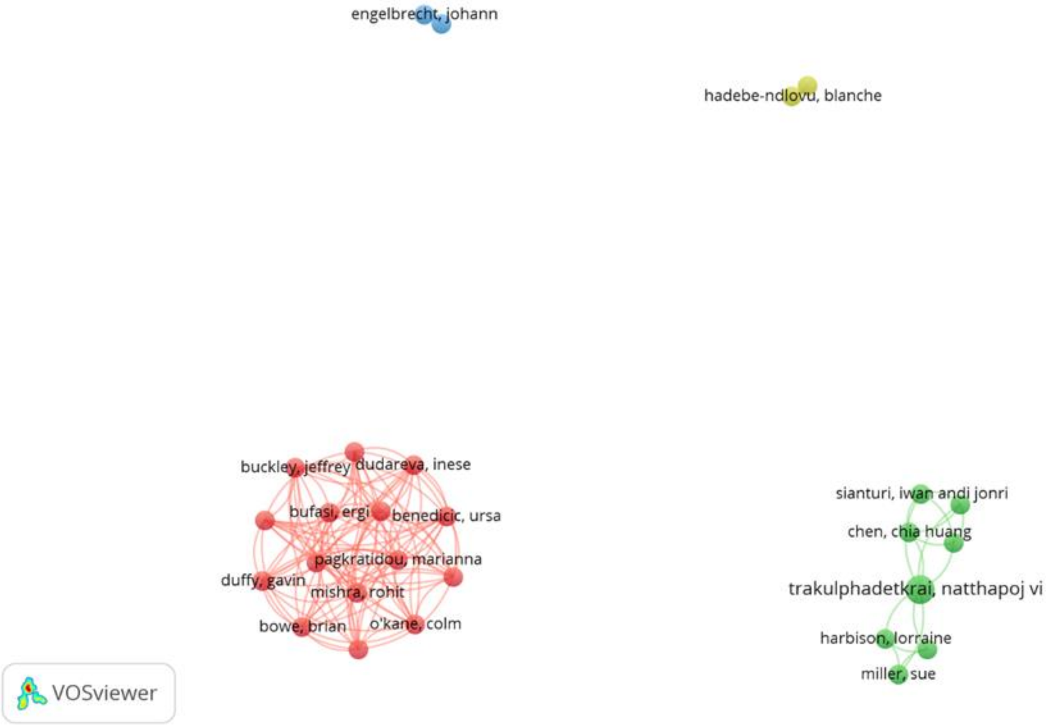

Figure 4 Author co-authorship network.

Note: This network visualization shows the relationships between authors, with larger nodes indicating authors who have higher collaboration strength and greater influence in early grade mathematics research.

Table 5 Top 10 dominant keywords in early grade mathematics research.

Rank	Keyword	Cluster	Description
1	Mathematics Education	4	Focuses on teaching strategies, curricula, and improving mathematics outcomes in early grades.
2	Mathematics	4	Core subject matter in early grade education, central to the research focus.
3	Teaching	4	Encompasses teaching practices and strategies for early grade mathematics education.
4	Collaboration	3	Refers to teamwork and cooperative efforts in enhancing mathematics teaching and learning.
5	Innovation	3	Incorporates new strategies, tools, and methods to advance teaching practices in mathematics.
6	Curriculum	2	Focus on designing and applying early grade mathematics curricula.
7	Lesson Study	2	A professional development method where educators collaboratively design and test lessons.
8	Grade R	2	Refers to the foundational year of education, focusing on early learning and mathematics development.
9	Barriers	1	Identifies challenges such as difficulties with spatial ability and word problems in early grade mathematics.
10	Word Problems	1	Specific challenges in teaching and solving word problems in early grade mathematics.

Note: The keywords are grouped by cluster, reflecting their association with the dominant research themes and challenges in early grade mathematics education.

Collectively, these dominant themes emphasize the enduring influence of Constructivist Learning Theory in shaping the early grade mathematics discourse (Piaget, 1952; Vygotsky, 1978). The recurring emphasis on teaching, collaboration, and curriculum reflects pedagogical approaches that position learners as active constructors of knowledge. However, the minimal presence of technology-related terms within the co-occurrence map reveals a notable research gap concerning digital and AI-enhanced pedagogies—an omission that limits alignment with Human Capital Theory's emphasis on preparing learners for a digital economy (Becker, 1993). Future bibliometric trends should therefore examine how AI-integrated instruction in foundational mathematics can bridge learning inequities and expand cognitive access.

3.3.2. Intellectual linkages and thematic clusters in early grade mathematics research

The ranking in Table 6 shows that Mullis, I.V.S. holds the top spot, reflecting a strong collaborative presence in early grade mathematics research, with the highest Total Link Strength. Shulman, L.S. and Lewis, C. follow closely, underscoring their significant contributions to the intellectual development of the field. Figure 6 visually reinforces this, with Mullis, I.V.S. and Shulman, L.S. occupying the largest nodes, indicating their central positions in the co-authorship network. Their research is pivotal in shaping the direction of early grade mathematics education. Other prominent authors such as Trakulphadetkrai, N.V., Graven, M., and Ball, D.L. play significant roles but with slightly less influence in terms of collaborative strength compared to the top-ranked authors. Nonetheless, they contribute to various aspects of teacher education, curriculum development, and research on barriers to learning in early mathematics.

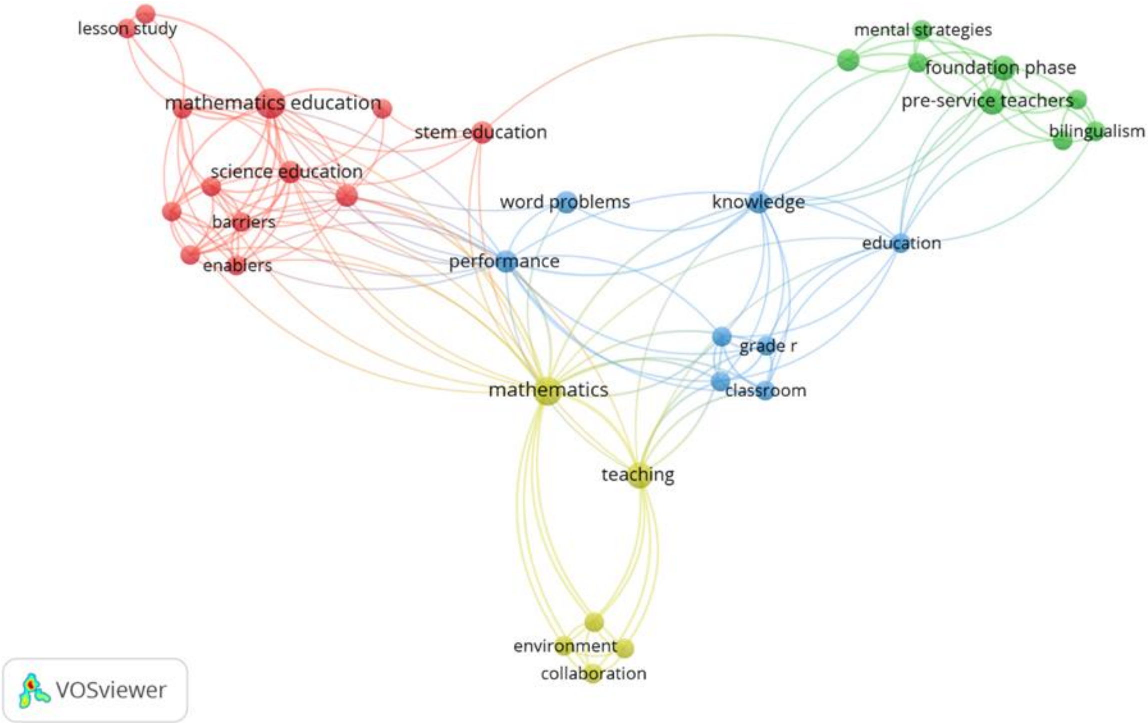

Figure 5 Co-occurrence map of keywords in early grade mathematics research.
Note: This map visualizes the relationships between frequently co-occurring keywords, revealing the dominant themes and research trends in the field. Larger clusters indicate higher co-occurrence, highlighting the centrality of these themes in early grade mathematics education.

Table 6 Top 10 authors in early grade mathematics research (ranked by co-authorship contribution).

Rank	Author	Cluster	Total Link Strength	Number of Documents
1	Mullis, I.V.S.	5	30	95
2	Shulman, L.S.	1	26	45
3	Lewis, C.	4	24	8
4	Liljedahl, P.	4	19	54
5	Trakulphadetkrai, N.V.	2	17	111
6	Ball, D.L.	4	16	24
7	Darling-Hammond, L.	3	16	57
8	Cochran-Smith, M.	3	15	45
9	Graven, M.	1	10	63
10	Mulligan, J.	4	6	3

The intellectual linkages dominated by scholars such as Mullis and Shulman mirror the theoretical duality of systemic measurement and pedagogical reflection. Their centrality affirms that early mathematics research is simultaneously informed by large-scale assessment frameworks (e.g., TIMSS) and teacher knowledge paradigms (Shulman, 1986), both of which converge on the need for evidence-based, developmentally responsive teaching.

3.4. Curriculum domains presenting the greatest learning challenges

Analysis of the studies in Table 2 indicates that the most challenging curriculum domains for learners in Grades R–2 are number sense, measurement, geometry, and problem-solving. Number sense and composition, especially skills such as subitising, grouping by ten, and moving from concrete to abstract representations, are frequently underdeveloped

(Nakawa et al., 2020; Vale & Westaway, 2024; Setoromo & Hadebe-Ndlovu, 2020). Word-problem solving presents additional hurdles, particularly when contexts are unfamiliar to learners from disadvantaged socioeconomic backgrounds (Schuchart et al., 2015). Learners also struggle with mental calculation and fluency, especially when strategies for bridging toward abstract numerical operations are not explicitly taught (Vale & Westaway, 2024). Early spatial reasoning skills, vital for geometry and measurement, often receive minimal attention, resulting in limited spatial awareness in young learners (Bufasi et al., 2024). Finally, language-mediated understanding of mathematical concepts poses a persistent barrier, particularly when instruction is delivered in non-native languages without sufficient scaffolding (Cekiso et al. 2019; Olawale et al., 2024).

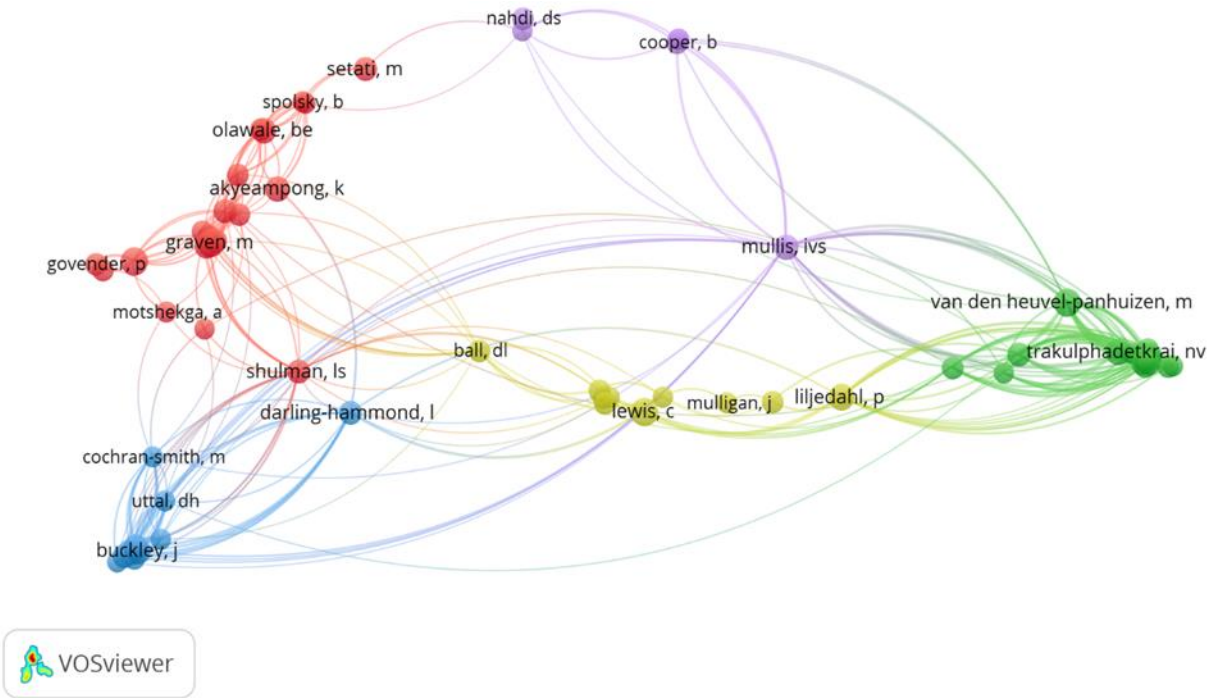

Figure 6 Co-authorship network of early grade mathematics authors.
Note: This visualization shows the collaborative connections between prominent authors in early grade mathematics research, highlighting the key contributors and their influence in shaping the field.

These findings substantiate Constructivist Learning Theory's premise that conceptual understanding emerges through active exploration and guided mediation (Vygotsky, 1978). When teaching fails to align with children's developmental stages, learners struggle to transition from concrete experiences to symbolic abstraction. Empirical work by Naroth and Luneta (2015) and Maboya et al. (2020) demonstrated that the CPA (Concrete–Pictorial–Abstract) approach and manipulatives foster deep reasoning and improved number sense—validating Vygotsky's notion of the Zone of Proximal Development (ZPD).

3.5. Key factors contributing to early mathematics difficulties

The studies summarised in Table 2 point to multiple, intersecting factors behind early mathematics learning challenges. Language mismatches between home and school environments, particularly where instruction is delivered in a second language, undermine learners' comprehension and conceptual access (Cekiso et al., 2019; Chitera & Loakes, 2012; Olawale et al., 2024). Teacher content knowledge and pedagogical content knowledge (PCK) often remain weak in early-grade classrooms, limiting the capacity to deliver effectively structured, conceptually rich instruction (Setoromo & Hadebe-Ndlovu, 2020; Maboya et al., 2020; Sekao & Engelbrecht, 2022). Socioeconomic disparities compound these issues; learners from lower-income backgrounds have reduced exposure to numerically rich contexts and mathematical language, affecting their performance, especially in word problems and numeracy-related reasoning (Schuchart et al., 2015; Hill & Dowker, 2016). Limited pedagogical and material resources, such as manipulatives, visual aids, and story-based curricula, further hinder development across domains (Maboya et al., 2020; Prendergast et al., 2019; Yang et al., 2021). Finally, professional development remains fragmented; while some contexts have adopted CPD models such as Lesson Study or mastery learning approaches (Naroth & Luneta, 2015; Sekao & Engelbrecht, 2022), many teachers still lack practical support to implement research-based practices such as CPA (Concrete–Pictorial–Abstract), mental strategy drills, and spatial tasks.

The persistence of these challenges reinforces Bronfenbrenner's (1979) Ecological Systems Theory, illustrating how microsystem factors (teacher knowledge and beliefs) and exosystem influences (resource allocation, institutional policy) interact to constrain effective pedagogy. Studies such as Sekao and Engelbrecht (2022) highlight how professional development models like Lesson Study can mediate these multilevel constraints by promoting collaborative reflection and contextualized problem-solving. Addressing such interconnected barriers therefore requires a systemic rather than isolated approach.

3.6. Implications for skills development and workforce planning

As evidenced in Table 2, foundational challenges in early mathematics have serious long-term implications for skills development and future workforce readiness. A key concern is that gaps in early numeracy skills, if not addressed, tend to persist and compound over time, limiting learners' ability to engage in more advanced mathematical thinking. For example, Hazell et al. (2019) demonstrated that early interventions such as the "R Maths" programme can lead to significant gains in early mathematical proficiency, suggesting that targeted support at this stage yields long-term educational returns. The success of such programmes implies that early numeracy is not only a foundational skill but also a critical gateway to later achievement and workforce competence. Furthermore, Nakawa et al. (2020) found that developing structural number sense, such as recognising groupings of ten, enhances learners' calculation skills beyond rote counting. These kinds of foundational skills are directly linked to learners' abilities to reason, problem-solve, and progress through the mathematics curriculum, skills that are vital in the modern labour market. Similarly, Vale and Westaway (2024) highlight how structured mental strategies can improve fluency in calculation, a core skill for lifelong numeracy and employability. Their findings reinforce the notion that planning for workforce skills must begin with robust, conceptually grounded early mathematics education. Finally, studies such as Setoromo & Hadebe-Ndlovu (2020) show that teachers limited mathematical knowledge in Grade R classrooms can hinder the development of foundational skills. Without addressing such foundational teacher capacity gaps, efforts to enhance early numeracy and its downstream effects on national skills pipelines may remain ineffective.

These implications resonate strongly with Human Capital Theory (Becker, 1993), which frames early mathematics education as an investment in long-term economic productivity. Strengthening foundational numeracy not only improves academic outcomes but also cultivates cognitive flexibility, problem-solving, and reasoning—skills essential for participation in modern knowledge economies. Empirical evidence from Hazell et al. (2019) and Nakawa et al. (2020) demonstrates that targeted early interventions yield measurable returns, underscoring the economic rationale for prioritizing foundational learning within national development agendas.

3.7. Curriculum, teacher training, and policy responses

The studies summarised in Table 2 reveal a range of efforts, both promising and problematic, across curriculum design, teacher training, and policy implementation aimed at improving early grade mathematics outcomes. One significant area of reform has been the push toward bilingual and language-responsive teaching strategies, especially in multilingual contexts like South Africa. Cekiso et al. (2019), for example, found that although teachers recognised the benefits of mother tongue instruction in mathematics, they often faced linguistic and resource-related challenges. In a similar vein, Olawale et al. (2024) underscore the importance of systematic translanguaging strategies in teacher preparation to bridge content and language gaps. Curriculum design efforts have also increasingly focused on conceptual and visual learning frameworks. The Concrete–Pictorial–Abstract (CPA) approach, studied by Naroth and Luneta (2015), facilitated deeper mathematical understanding across ability levels using manipulatives and visual learning strategies. This approach reflects an important shift toward mastery-based learning in the Foundation Phase. Similarly, Maboya et al. (2020) emphasized the pedagogical value of manipulatives in developing abstract-symbolic understanding, highlighting the role of teacher beliefs in mediating instructional quality. Professional development initiatives like Lesson Study, as explored by Sekao and Engelbrecht (2022), have shown potential in building collaborative teaching practices, though they are often hindered by resource constraints and lack of institutional support. Teacher preparation in specific mathematical domains has also improved through targeted interventions; for example, Vale and Westaway (2024) showed that pre-service teachers developed key mental calculation competencies using structured materials like MSAP. Despite these advances, gaps remain. As noted by Chitera and Loakes (2012) in the Malawian context, policy-practice mismatches, particularly around language-in-education, can undermine teacher confidence and effectiveness. This points to the critical need for greater alignment between curriculum frameworks, teacher education programmes, and language policies to ensure coherence in mathematics instruction.

These findings collectively underscore that sustainable improvement in early grade mathematics depends on policy coherence across curriculum design, teacher preparation, and language-in-education frameworks. The Ecological Systems Theory perspective emphasizes that reform success requires alignment between macrosystem policies and microsystem practices (Bronfenbrenner, 1979). Integrating translanguaging strategies (Olawale et al., 2024), CPA pedagogy (Naroth & Luneta, 2015), and collaborative professional development models (Sekao & Engelbrecht, 2022) within teacher education can bridge this gap and support more equitable learning outcomes.

4. Final Considerations

The findings of this study reveal a significant increase in scholarly attention to early grade mathematics over the past decade, particularly after 2015, reflecting a global emphasis on foundational learning as a cornerstone for educational equity and economic development. However, the research landscape remains geographically concentrated, with South Africa leading contributions, while other low- and middle-income contexts remain underrepresented. Thematic analysis highlighted persistent challenges faced by learners in number sense development, problem-solving, and mental calculation, often linked to factors such as inadequate teacher content knowledge, language barriers, and limited access to instructional resources.

Teacher professional development and curriculum innovation emerged as dominant themes, with collaborative pedagogies like Lesson Study and CPA (Concrete–Pictorial–Abstract) approaches frequently cited as effective strategies for enhancing instructional quality. Despite these advancements, systemic barriers such as fragmented policy implementation, resource constraints, and gaps in teacher preparation continue to hinder progress.

The bibliometric analysis further exposed thematic gaps in the integration of technology-driven instructional innovations, including AI-enhanced learning tools, indicating a disconnect between emerging educational technologies and foundational mathematics research. Addressing these challenges requires coordinated efforts that align curriculum design, teacher capacity-building, and policy coherence, while fostering inclusive research collaborations across diverse educational contexts. Such an integrated approach is essential to strengthen foundational numeracy, reduce learning disparities, and equip learners with the competencies required for active participation in an increasingly digital and knowledge-driven economy.

To address the persistent challenges in early grade mathematics, there is a critical need for systemic and multi-level interventions that prioritize both pedagogical and structural reforms. First, teacher professional development should be strengthened through targeted programmes that build both content knowledge and pedagogical content knowledge, with a particular focus on early numeracy concepts such as number sense, mental calculation strategies, and problem-solving approaches. Professional development models such as Lesson Study and mastery-based training should be scaled and embedded within national continuous professional development frameworks, ensuring that teachers are equipped with practical, classroom-applicable skills.

Curriculum design should also be revisited to emphasize conceptual understanding through the integration of CPA (Concrete–Pictorial–Abstract) instructional strategies and the use of manipulatives that support learners' cognitive development. Additionally, language-in-education policies should be aligned with classroom realities by promoting mother-tongue instruction in the early grades and providing systematic support for translanguaging strategies. This requires the development of localized instructional materials and resources that bridge language gaps and enhance conceptual access for learners.

Moreover, policy coherence and resource allocation are essential to ensure that effective teaching practices identified in research are translated into classroom realities. Governments and educational institutions should invest in resource provisioning, including teaching aids, digital tools, and contextually relevant assessment instruments that support differentiated instruction.

An important gap identified in the research landscape is the limited focus on technology-driven pedagogies, particularly the integration of AI-assisted learning tools in foundational mathematics education. Future research and pilot initiatives should explore the development of AI-augmented educational platforms that provide real-time feedback, personalized learning pathways, and interactive visualizations to support both teachers and learners in the early grades. Encouraging cross-disciplinary collaborations between educational researchers, technology developers, and policymakers will be critical in bridging this innovation gap.

Finally, fostering inclusive research collaborations that amplify underrepresented regions and contexts is essential for building a diversified and contextually relevant evidence base. Such efforts will not only enrich the global discourse on foundational numeracy but also inform more equitable and effective educational policies and interventions.

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Ethical Considerations

Not applicable.

Conflict of Interest

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