Pedagogical Research
2026, 11(3), em0282
e-ISSN: 2468-4929
https://www.pedagogicalresearch.com

MODESTUM

Review Article

OPEN ACCESS

Research trends and intellectual structure of early childhood mathematical development: A bibliometric analysis (2006–2025)

Feriha Hande İdil [1] *, Sibel Yeşildere İmre [2]

[1] Izmir Provincial Directorate of National Education, TÜRKİYE
[2] Dokuz Eylül University, TÜRKİYE
***Corresponding Author:** deuhande@gmail.com

Citation: İdil, F. H., & Yeşildere İmre, S. (2026). Research trends and intellectual structure of early childhood mathematical development: A bibliometric analysis (2006–2025). *Pedagogical Research, 11*(3), em0282. https://doi.org/10.29333/pr/19101

ARTICLE INFO

Received: 27 Feb. 2026

Accepted: 05 Jun. 2026

ABSTRACT

Mathematical skills acquired during early childhood are widely recognized as strong predictors of later academic achievement. However, studies systematically mapping the global knowledge structure of research on preschool mathematical development remain limited. This study examined 143 academic publications from the Web of Science (WoS) database between 2006 and 2025 using bibliometric analysis, aiming to provide a comprehensive, integrated structural map of the field. Publication trends, author, country, and institution distributions, citation patterns, and keyword co-occurrence clusters were analyzed using VOSviewer 1.6.20. Findings revealed a significant increase in publications after 2015, with the United States, Germany, and Belgium as leading countries, and KU Leuven as the most productive institution. A longitudinal study on executive functions received the highest number of citations. Keyword analysis demonstrated that executive functions and cognitive processes constitute the dominant research focus; however, notable gaps exist in digital technology integration, cross-cultural perspectives, and play-based learning approaches.

Keywords: preschool, mathematical development, early childhood education, bibliometric analysis, mathematical achievement

INTRODUCTION

The preschool period represents a critical developmental phase in which the foundations of cognitive, social, and academic competence are established. Early childhood education supports children's holistic development and contributes significantly to later academic achievement (Kağıtçıbaşı et al., 2001). Yet the relationship between early education and long-term outcomes is not uniform across developmental domains. A landmark synthesis by Duncan et al. (2007), drawing on six large longitudinal datasets, established that early mathematics skills are the single strongest predictor of later academic achievement—outperforming early reading, attention, and socioemotional skills in predictive power. This finding has since been replicated and extended: Watts et al. (2014) demonstrated that early mathematics knowledge predicts high school achievement even after controlling for a wide range of background variables, while Claessens et al. (2009) showed that kindergarten mathematics skills remain a significant predictor of fifth-grade outcomes beyond the influence of early literacy. Crucially, this body of evidence is not merely correlational. Experimental studies have demonstrated that structured early mathematics interventions produce lasting gains in achievement trajectories (Clements & Sarama, 2011; Starkey et al., 2004), suggesting that the relationship between early mathematical competence and later achievement is at least partly causal and therefore amenable to pedagogical intervention. Together, these strands of evidence converge on a clear theoretical and policy conclusion: mathematical development during the preschool years is not simply a developmental precursor but a critical lever for long-term academic equity.

Preschool mathematical development refers to the processes through which children aged 3–6 acquire and apply fundamental mathematical skills, including number concepts, pattern recognition, spatial reasoning, and problem-solving (Clements & Sarama, 2009). These competencies do not develop in isolation; they are embedded within a broader cognitive architecture that includes executive functions, working memory, and attentional control (Blair & Razza, 2007; Fuchs et al., 2010). The theoretical significance of this interconnection has been elaborated by Bull et al. (2008), whose longitudinal study demonstrated that working memory and executive functioning assessed at preschool age are significant predictors of mathematical achievement at age 7—even after controlling for general intelligence. This finding repositioned early mathematics research within a cognitive developmental framework, linking numerical competence to domain-general regulatory processes rather than treating it as a purely content-specific skill. The practical implication is substantial: interventions that simultaneously

target executive functions and early mathematical knowledge may yield broader and more durable cognitive benefits than those focused on numerical content alone (Blair & Razza, 2007; Fuchs et al., 2010).

Over the past decade, preschool mathematics education has attracted increasing scholarly attention at national and international levels. A recent bibliometric study examining 748 publications between 2015 and 2025 demonstrated that academic production in the field has expanded considerably, with noticeable peaks in output and growing international collaboration networks (İdil & Yıldırım, 2025). The same study highlighted that executive functions, early number competence, and spatial reasoning have become central thematic clusters within the knowledge structure of preschool mathematics education. These findings confirm that the field is evolving into an interdisciplinary research domain shaped by cognitive, pedagogical, and developmental perspectives.

Despite this growth, two structural limitations constrain the current knowledge base. First, existing reviews tend to concentrate on specific subtopics—such as number sense or executive functions—rather than providing an integrated structural overview of the field as a whole. This fragmentation makes it difficult to identify cross-cutting patterns, evaluate the relative weight of competing research traditions, or detect systematic absences in the literature. Second, no prior bibliometric study has mapped preschool mathematical development as a distinct research domain across a sustained, multidimensional horizon. İdil and Yıldırım (2025) address preschool mathematics education broadly rather than focusing specifically on mathematical development as a theoretically coherent construct, while remaining comprehensive in scope. This distinction matters: mathematical development, as a concept, foregrounds cognitive, longitudinal, and neurodevelopmental dimensions that are not always central to broader educational bibliometric analyses. A dedicated structural map of this construct is therefore both theoretically warranted and practically necessary.

Bibliometric analysis offers a systematic and quantitative approach to examining these dimensions within a research domain (Meiliati et al., 2026; Siregar et al., 2026; Zupic & Čater, 2015). By identifying influential works, conceptual clusters, and research gaps, bibliometric methods provide insight into the intellectual structure and evolution of a field. The term 'multidimensional,' as used in this study, refers to the simultaneous examination of structural, thematic, geographic, temporal, and impact-related dimensions of the literature—including publication trends, authorship and collaboration networks, institutional and national outputs, citation influence, and keyword co-occurrence patterns. This integrative approach contrasts with single-dimensional analyses that address only one or two of these aspects and allows for a more complete picture of how knowledge in a field is produced, structured, and distributed.

The primary objective of this study is to examine academic production in the field of preschool mathematical development from a multidimensional perspective by identifying publication trends, thematic concentrations, collaboration patterns, and citation impact. By providing a comprehensive structural map of the field over 20 years, this study aims to clarify its intellectual landscape, reveal conceptual and geographic gaps, and offer an evidence-based framework to guide future research priorities and policy development. Importantly, this study is not conceived as a mere mapping exercise. Rather, it seeks to interpret structural patterns in light of theoretical developments in the field, thereby producing insights that extend beyond what descriptive bibliometric mapping alone can offer. The aspiration is to produce what Zupic and Čater (2015) describe as a 'science map'—a representation of the field that is simultaneously descriptive, evaluative, and generative of new research questions.

The sub-problems guiding this study are as follows: (1) How has academic production in the field of preschool mathematical development evolved in terms of publication volume and type? (2) Who are the most productive and most cited authors, countries, and institutions, and what collaboration patterns characterize the field? (3) What are the most influential publications in the field, and what thematic patterns do they reflect? (4) What are the dominant conceptual clusters in the literature, and how have these thematic emphases shifted over the period 2006–2025? (5) What research gaps exist, and what future directions do they suggest?

METHOD

Research Design

This research systematically examined academic publications on mathematical development during the preschool period. A descriptive survey model and a quantitative research design were employed. The survey model aims to describe a phenomenon within its existing conditions, without external intervention, and to analyze events in their natural settings (Karasar, 2005). The bibliometric analysis method was adopted accordingly. Bibliometric analysis evaluates the bibliographic characteristics of academic publications using quantitative criteria and reveals publication volume, conceptual trends, citation levels, collaboration structures, and research gaps (Hawkins, 2001; Zupic & Čater, 2015). This technique is widely preferred for identifying growth trends, determining influential authors and institutions, and analyzing relationships between knowledge clusters (Chuang et al., 2007; Donthu et al., 2021).

Data Source and Sample

The Web of Science (WoS) Core Collection was selected as the data source for this study due to its high reliability, comprehensive coverage, and established role as a standard reference for bibliometric research. WoS provides bibliographic traceability of international academic literature across a wide disciplinary spectrum and enables detailed examination of citations, author profiles, and institutional affiliations (Falagas et al., 2008). The decision to use WoS as the sole database reflects both its recognized authority for bibliometric mapping studies (Donthu et al., 2021) and its systematic indexing of high-quality peer-reviewed publications across social sciences and education. While this choice has implications for coverage—discussed under Limitations—it ensures consistency and replicability in the bibliometric indicators computed.

The sample comprises 143 academic publications in the WoS Core Collection, published between 2006 and 2025, that address preschool mathematical development. Purposive sampling was used; the target population was defined by applying specific inclusion and exclusion criteria. The year 2006 was selected as the starting point for three converging reasons. Methodologically, it marks the period when VOSviewer and other modern bibliometric tools became widely adopted, enabling comparable and reproducible network analyses. Substantively, Duncan et al.'s (2007) landmark study—which established the predictive superiority of early mathematics over other school-readiness skills—was in preparation and pre-publication circulation during this period, making 2006 a theoretically meaningful threshold that captures the field just before its most influential paradigmatic contribution. Database-driven WoS coverage and indexing density for education journals improved substantially from this period onward, reducing the risk of systematic underrepresentation in earlier years.

Data Collection Process

Data collection was conducted in July 2025 and involved the following steps.

Search strategy

All collections in the WoS database were considered: Science Citation Index Expanded (SCI-Expanded), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (AHCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index – Science (CPCI-S), Conference Proceedings Citation Index – Social Science & Humanities (CPCI-SSH), Book Citation Index – Science (BKCI-S), and Book Citation Index – Social Sciences & Humanities (BKCI-SSH). This broad inclusion targeted high interdisciplinary coverage. The search string was:

> TS= ((preschool OR "pre-school" OR "early childhood" OR kindergarten OR "pre-kindergarten") AND ("mathematical development" OR "mathematics development" OR "math development" OR "Mathematical achievement" OR "mathematics achievement" OR "math achievement" OR "Mathematical skills" OR "mathematics skills" OR "numeracy" OR "number sense" OR "Early mathematics" OR "early math"))

In this search string: TS (Topic Search) scanned title, abstract, keywords, and Keywords Plus fields; OR operators included synonymous concepts; AND operators ensured intersection of the two main concept sets; and quotation marks ensured exact phrase matching.

Inclusion and exclusion criteria

Publications were included if they: (a) were published between 2006 and 2025; (b) were topically relevant to mathematical development, mathematics education, or mathematical skills in the preschool period, operationally defined as children aged 3–6 years; and (c) belonged to eligible publication types: articles, proceedings papers, review articles, early access publications, book chapters, or editorial materials. No language restrictions were imposed, and full-text access was not required, as bibliographic information was sufficient for analysis. Publications focused on primary school age groups (typically age 6 and above) were excluded. It is important to clarify that although some included documents referenced primary school age as a boundary condition, this was used solely as an exclusion threshold to demarcate the upper boundary of the preschool period. All included studies concerned children within the 3–6 age range or explicitly identified their sample as preschool-aged. Additional exclusion criteria comprised: studies addressing developmental domains other than mathematical development; publications with incomplete or erroneous bibliographic information; and duplicate records identified during data cleaning.

Data Analysis

The findings section is organized according to the five sub-problems identified above, progressing from descriptive indicators—publication volume and type, author/country/institution distributions—to relational and conceptual analyses including citation networks, co-authorship structures, and keyword clusters. This sequential structure is not merely organizational; it reflects a deliberate analytical logic in which surface-level patterns (who publishes, where, how much) provide the evidentiary base for deeper interpretive claims about the field's intellectual structure and theoretical orientation.

In the first stage, bibliographic data were categorized by publication year, author names, country and institution, keywords, and citation counts. These were classified, described, and visualized using frequency and percentage analyses in Microsoft Excel 2021. Citation analysis serves not merely as a count of academic attention but as a theoretically meaningful indicator of scholarly influence: high citation counts reflect the degree to which a publication has shaped subsequent research agendas, and differential citation patterns across authors, countries, and institutions reveal the structural inequalities and concentration of epistemic authority that characterize the field's knowledge production dynamics (Donthu et al., 2021).

In the second stage, bibliometric network analysis was conducted using VOSviewer (Version 1.6.20). Co-authorship analysis was conducted with a minimum threshold of 1 publication and 1 citation, and the results were visualized using network and density maps. Citation analysis used a minimum of 20 citations per document. Keyword co-occurrence analysis applied a minimum occurrence threshold of two. Clustering was performed using VOSviewer's default algorithm, with a resolution parameter set to 1.0 and a minimum cluster size of three nodes.

Prior to analysis, data quality procedures included: correction of inconsistencies in author names (e.g., merging 'Smith, J.' and 'Smith, John'), standardization of institution name variations, merging of keyword synonyms (e.g., 'preschool' and 'pre-school'), and removal of duplicate records. Validity and reliability were ensured through the use of WoS, an internationally recognized database; systematic, reproducible search protocols; VOSviewer, a validated tool; and rigorous data consistency controls.

FINDINGS

This section presents findings organized according to the five research sub-problems. Sub-section one addresses publication trends and types (Sub-problem 1). Sub-section two examines author, country, and institutional productivity alongside citation impact and co-authorship networks (Sub-problem 2). Sub-section three identifies the most influential publications and interprets their thematic significance (Sub-problem 3). Sub-section four presents keyword co-occurrence and temporal thematic analysis (Sub-problems 4 and 5). Throughout, descriptive data are interpreted in relation to the research problem rather than reported in isolation to build a theoretically grounded account of the field's intellectual architecture.

Distribution by Years and Publication Types

Distribution by years

The distribution of academic publications by year reveals distinct trends in the field's development. The highest number of publications was recorded in 2018 (f = 14; 9.79%), followed by 2015, 2020, and 2025 (each f = 13; 9.09%). Other notable years are 2021 (f = 12; 8.39%), 2017 (f = 11; 7.69%), and 2016 (f = 10; 6.99%) (see **Figure 1**).

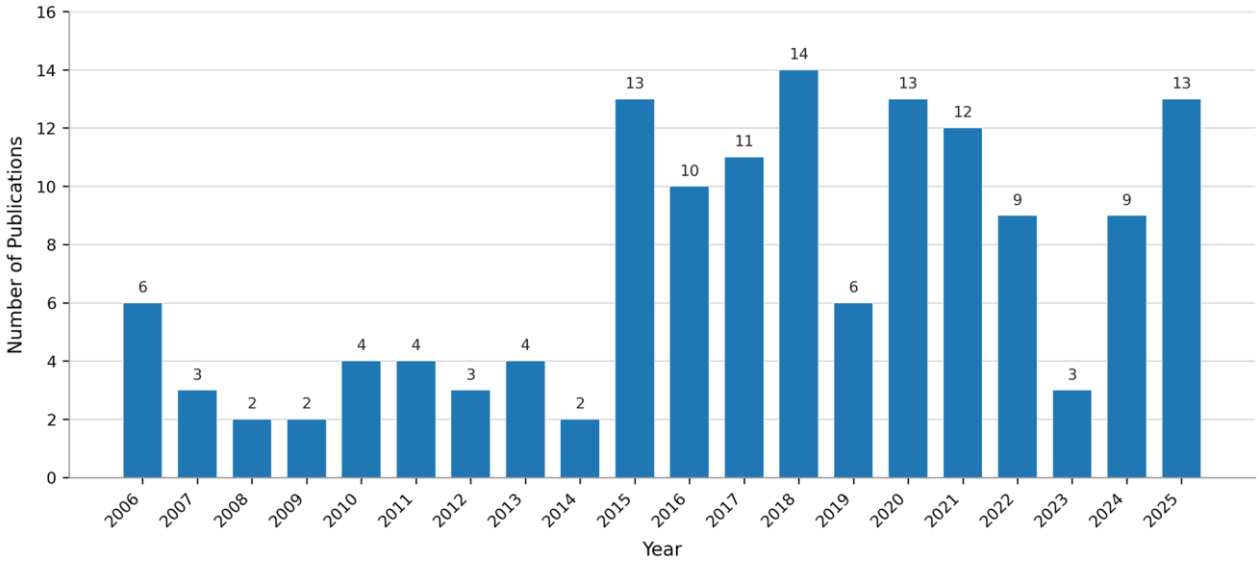

Figure 1. Numerical distribution of academic publications themed on preschool mathematical development by years (WoS, July 2025) (Source: Authors' own elaboration)

Publications remained low and unstable between 2006 and 2014, totalling 30 publications (annual average: 3.3). From 2015 onward, output shifted to a markedly higher level: the 2015-2025 period accounts for 113 publications, with an annual average of 10.3-approximately a threefold increase in academic interest. This shift is best characterised as a change in level rather than a steady upward trajectory, as annual output within the later period fluctuates considerably (range: 3-14). As data for 2025 were compiled as of July, publication counts for this year are expected to increase. This growth pattern is not incidental; it reflects a convergence of scientific, institutional, and policy forces. Scientifically, the post-2015 surge coincides with the consolidation of longitudinal evidence demonstrating that early mathematics is a uniquely powerful predictor of long-term academic outcomes (Duncan et al., 2007; Watts et al., 2018). Institutionally, the OECD's and UNESCO's heightened emphasis on early childhood education after 2010, combined with Heckman's (2006) economic analyses demonstrating the high return on investment of early interventions, created strong incentives for research funding in this area. The result was not merely more publications but a qualitative shift in research ambition: the field moved from documenting the existence of early mathematical competencies to investigating their cognitive underpinnings, malleability, and long-term consequences. This interpretive reading is supported by the keyword temporal analysis presented later in this section, which shows a clear thematic evolution from basic skills documentation toward cognitive mechanisms and, most recently, interdisciplinary integration.

Distribution by publication types

Journal articles constitute the vast majority of the literature (f = 130; 90.91%), followed by proceedings papers (f = 8; 5.59%), review articles (f = 6; 4.20%), early access publications (f = 5; 3.50%), book chapters (f = 1; 0.70%), and editorial materials (f = 1; 0.70%) (see **Figure 2**). Because WoS assigns more than one document-type label to some records, these categories total 151 labels across the 143 publications; percentages are therefore calculated over the corpus and sum to slightly more than 100%.

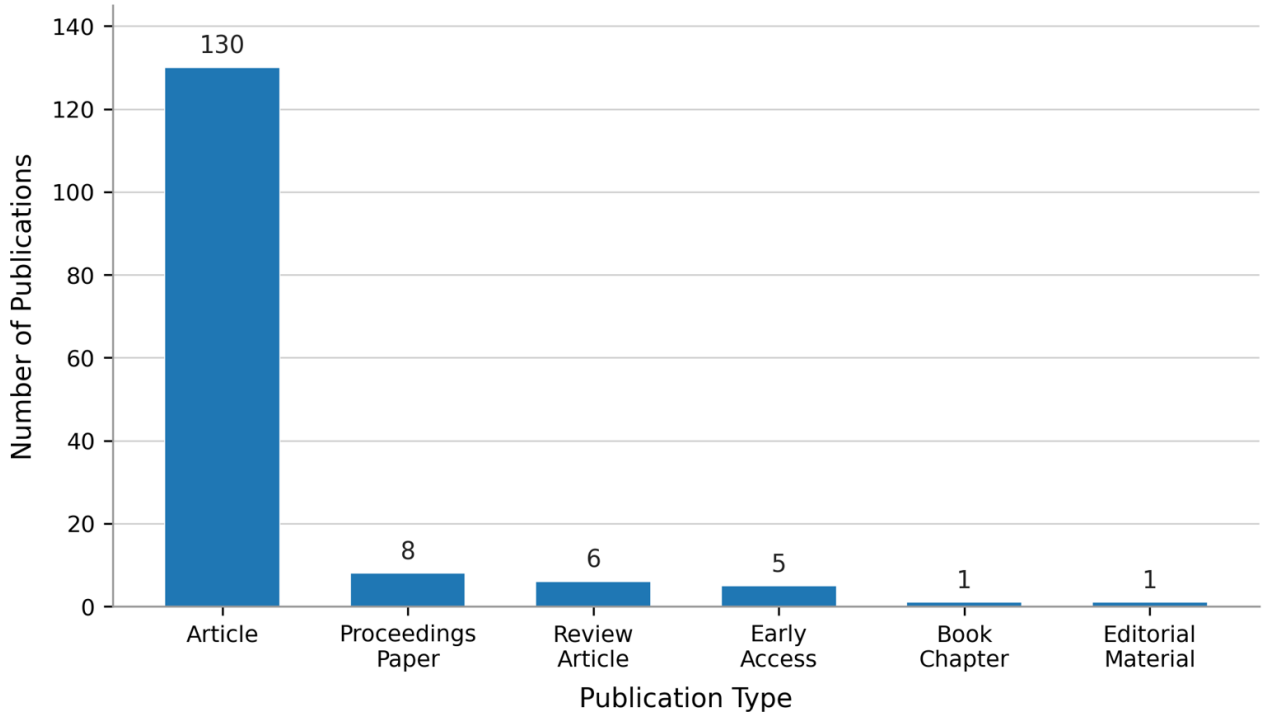

Figure 2. Numerical distribution of publications on preschool mathematical development by types (WoS, July 2025) (Source: Authors' own elaboration)

The overwhelming dominance of empirical journal articles (90.91%) indicates that the field has developed a strong peer-reviewed empirical core-a characteristic of scientifically mature research domains (Donthu et al., 2021). However, the very low proportion of review articles (4.20%) and book chapters (0.70%-a single publication across the entire 20-year period) is a structurally significant finding, suggesting that investment in synthesis and theory-building has not matched the accumulation of empirical evidence. Bibliometric evidence from early childhood education research similarly indicates that empirically productive fields face structural challenges in synthesis, sustained scholarly output, and thematic diversification (Halmatov et al., 2026); without review articles and integrative theoretical work, empirical findings risk remaining fragmented rather than coalescing into coherent frameworks. The limited share of conference proceedings (5.59%) further indicates that scholarly exchange in this field occurs predominantly through the formal journal literature rather than through conference-based debate, while early access publications (3.50%) reflect the influence of the open science movement and the accelerating pace of current research dissemination. Taken together, this distribution suggests a field that is empirically productive but theoretically underconsolidated-a pattern that itself represents an important research gap.

Distribution and Citation Analyses by Authors, Countries, and Institutions

Distribution by authors

A total of 408 different authors contributed to the 143 publications analyzed. Verschaffel L. (f = 9; 6.29%), Torbeyns J. (f = 8; 5.59%), and De Smedt B. (f = 7; 4.90%) are the three most productive authors (See **Figure 3**). All three are affiliated with KU Leuven, pointing to a strong and cohesive institutional research group.

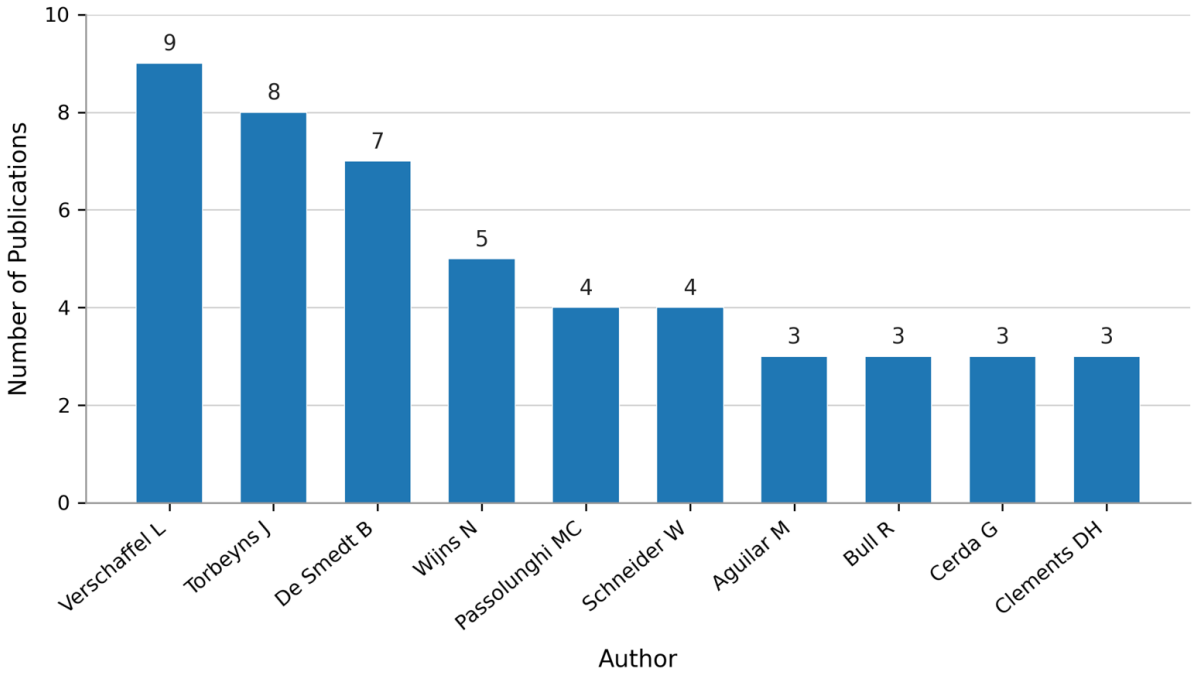

Figure 3. Distribution of publications focused on mathematical development during the preschool period by authors - Top 10 authors (WoS, July 2025) (Source: Authors' own elaboration)

Of the 408 contributing authors, only ten produced three or more publications, together accounting for 49 author-level publication attributions. Because publications are frequently co-authored, these attributions overlap substantially-the four KU Leuven authors in this group alone account for 29 attributions across the institution's 14 publications-and should therefore be read as indicators of individual visibility rather than as distinct shares of the corpus. Even allowing for this overlap, the distribution has a theoretically meaningful interpretation: it reflects a field organized around a small number of well-resourced, programmatic research groups that set the thematic agenda, surrounded by a much larger community of researchers, the overwhelming majority of whom contributed only one or two publications, who engage with-and extend-that agenda from diverse disciplinary and institutional vantage points. This is a structurally healthy pattern for a maturing field, as it combines the efficiency of focused expertise with the breadth of diverse perspectives (Chuang et al., 2007). It also carries a risk, however: if the dominant research groups operate within a shared paradigm—as the KU Leuven group's focus on cognitive and numerical competencies suggests—the field's thematic range may be implicitly constrained by the assumptions embedded in that paradigm.

Citation analysis of authors

A citation network map was generated with the criterion of at least one publication and one citation, yielding 175 interconnected units, 24 clusters, 322 links, and a total link strength of 337 (**Figure 4**). The most cited authors are Rebecca Bull, Kimberly Andrews Espy, and Sandra A. Wiebe, each credited with 1,118 citations, all deriving from a single co-authored publication. These authors also rank highest in total link strength.

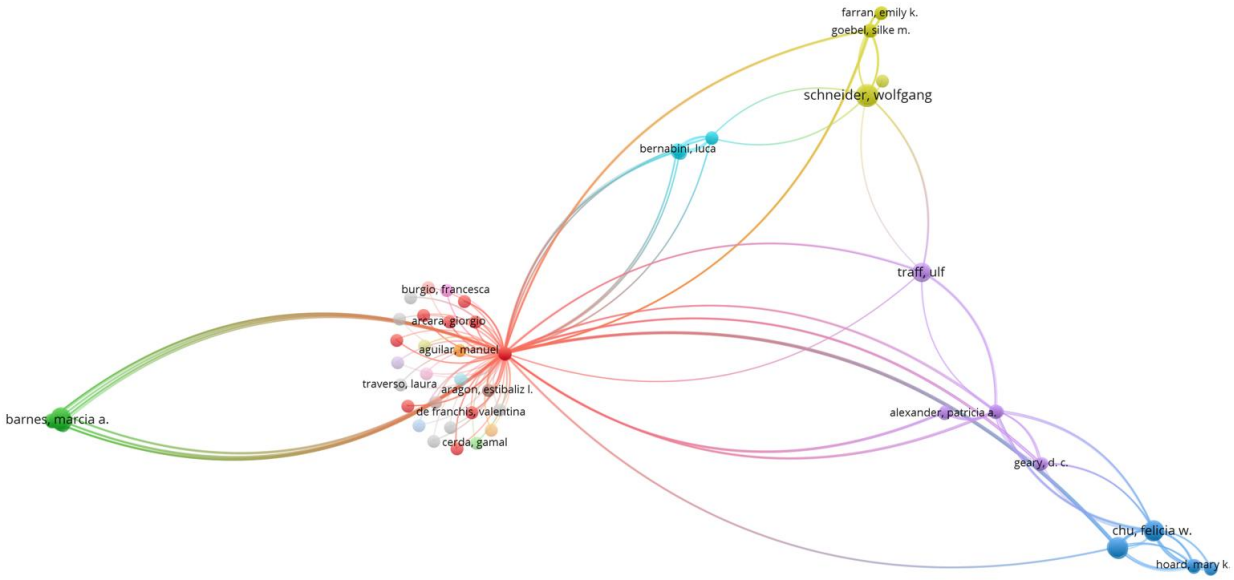

Figure 4. Citation analysis of authors (WoS, July 2025) (Source: Authors' own elaboration, using VOSviewer)

The dissociation between the most productive authors (Verschaffel, Torbeyns, De Smedt) and the most cited authors (Bull, Espy, Wiebe) is one of the most theoretically significant findings of this study. It reveals that academic influence in this field is not a simple function of publication volume. Bull et al.'s (2008) single longitudinal study, which traced the relationship between preschool executive functioning and mathematical achievement at age 7, generated more citations than the entire combined output of the field's most prolific authors. This pattern suggests that the field's intellectual agenda has been shaped primarily by paradigm-defining contributions—studies that opened new theoretical territories—rather than by sustained programmatic output. From a sociology of science perspective (Kuhn, 1970), this is characteristic of a field in a phase of paradigm consolidation: a small number of foundational works define the conceptual landscape, and subsequent research operates largely within the framework they established. The practical implication for researchers is clear: in a field where citation impact reflects theoretical originality rather than output volume, methodological rigor and theoretical ambition are more important determinants of scholarly influence than productivity alone (Chuang et al., 2007; Donthu et al., 2021).

Distribution by countries

Contributions from 34 countries were identified. The United States leads with 36 publications (25.17%), followed by Germany (f = 17; 11.89%) and Belgium (f = 15; 10.49%). England (f = 13; 9.09%) and Spain (f = 9; 6.29%) are also prominent (See **Figure 5**). The ten most productive countries together account for 125 country-level publication attributions; because publications with authors from more than one country are attributed to each, these counts overlap and exceed the number of distinct publications they represent. Seven of these ten countries are located in North America or Europe, reflecting a strong geographic concentration of research output.

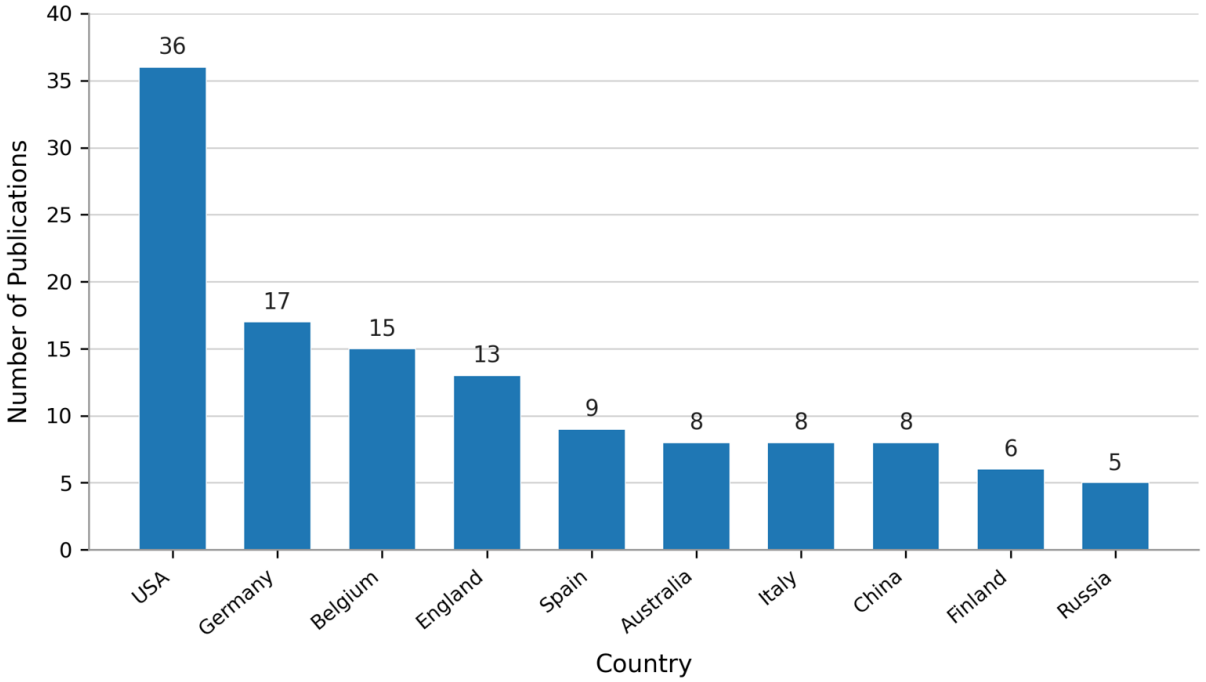

Figure 5. Countries where publications focused on mathematical development during the preschool period were published - Top 10 countries (WoS, July 2025) (Source: Authors' own elaboration)

This concentration is not merely a bibliometric fact; it is a substantive epistemological limitation. Research on preschool mathematical development has been conducted predominantly in contexts characterized by specific cultural values around early schooling, specific family structures, and specific levels of educational infrastructure. The near-absence of contributions from Sub-Saharan Africa, Southeast Asia, and Latin America means that the field's theoretical models, assessment instruments, and intervention designs have been developed and validated within a restricted range of cultural, linguistic, and socioeconomic contexts. This matters because numerical development is not culturally neutral: the structure of a language's number words, cultural practices around counting and arithmetic, and the economic value placed on formal mathematical knowledge all vary substantially across cultures and have been shown to influence early mathematical competence (Clements & Sarama, 2009). The geographic concentration of the literature therefore raises a fundamental question about the generalizability of its central findings—a question that the field has not yet systematically addressed. Critically, this limitation is compounded by the WoS database's known bias toward English-language, Western journals, meaning that research conducted in underrepresented regions may exist but remain invisible within the current bibliometric landscape (Falagas et al., 2008). These findings mirror broader inequalities documented in global scientific production (King, 2004; Moral-Muñoz et al., 2020) but carry particular weight for a field whose subject matter—early childhood mathematical competence—is inherently shaped by cultural context.

Citation analysis of countries

Citation analysis was conducted for 20 countries that met the threshold of at least one publication and one citation, yielding 7 clusters, 25 links, and 59 total link strength (**Figure 6**). The United States leads with 2,917 citations, followed by Scotland (1,118) and England (573).

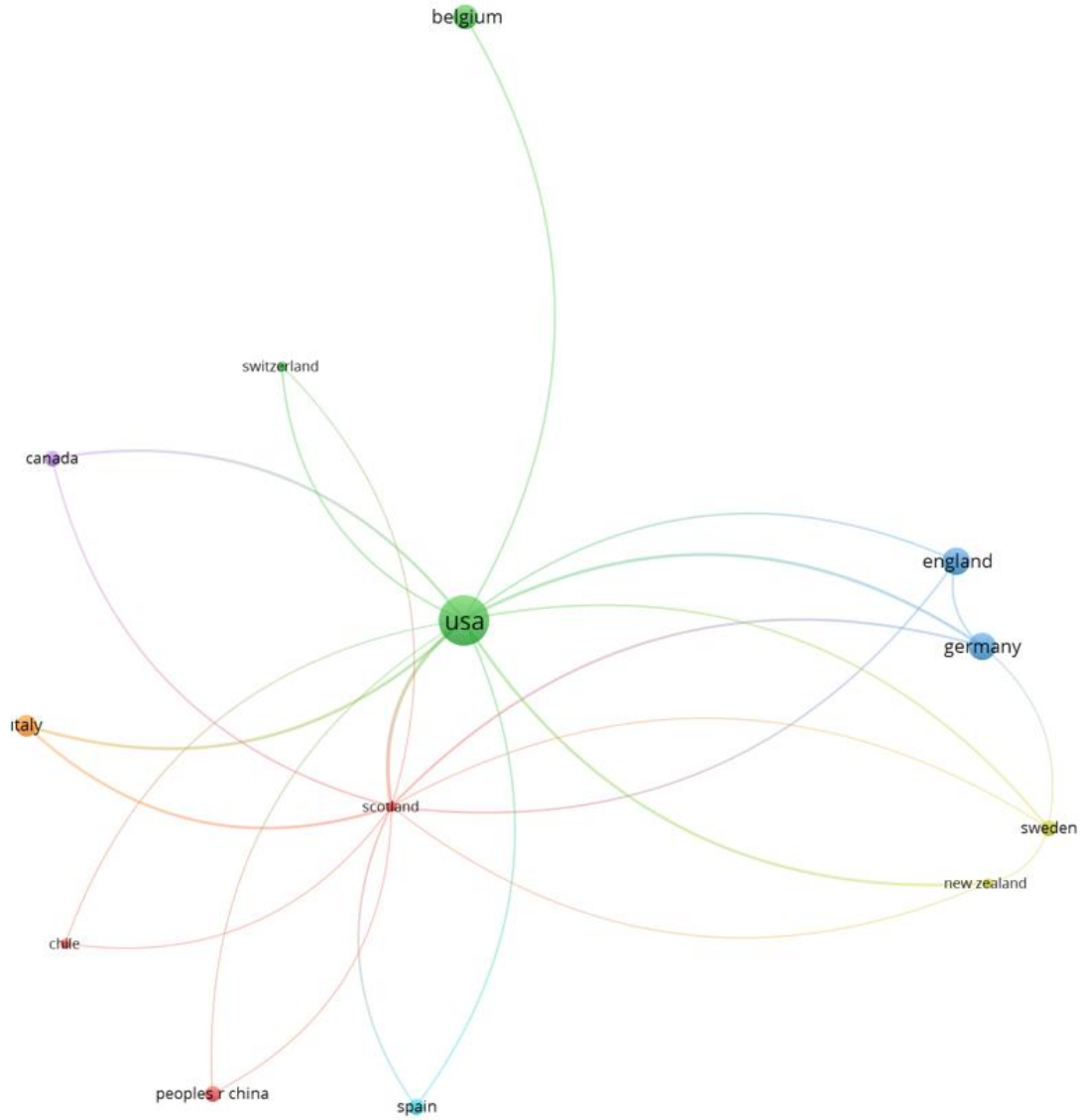

Figure 6. Citation analysis of countries (WoS, July 2025) (Source: Authors' own elaboration, using VOSviewer)

Scotland's second-place citation ranking—despite not appearing among the top 10 countries in publication volume—is a structurally instructive finding that reinforces the productivity-impact dissociation observed at the author level. Scotland's disproportionate citation impact derives almost entirely from Bull et al.'s (2008) study at the University of Aberdeen, a single publication that generated 1,118 citations. This case demonstrates that citation impact at the country level can be driven by individual high-impact studies rather than by broad national research infrastructure. It also illustrates a broader principle: in scientifically young or focused fields, paradigm-defining contributions by small teams can outweigh the aggregate output of large national research programs. This principle has direct implications for how research funding agencies in smaller countries should evaluate investment in focused, theoretically ambitious research programs.

Distribution by institutions

Contributions from 198 different institutions were identified. KU Leuven leads in publication output (f = 14; 9.79%), followed by the University of California System (f = 7; 4.90%), and the University of London and University of Texas System (each f = 6; 4.20%). (See **Figure 7**). The ten most productive institutions together account for 63 institution-level publication attributions. These counts should be interpreted with caution, as WoS indexes university systems and their constituent institutions separately, so the top-10 list includes partially overlapping entities (e.g., University of California System and University of California Irvine; University of London and University College London). Even allowing for this overlap, a limited set of research centres accounts for a substantial share of the field's output.

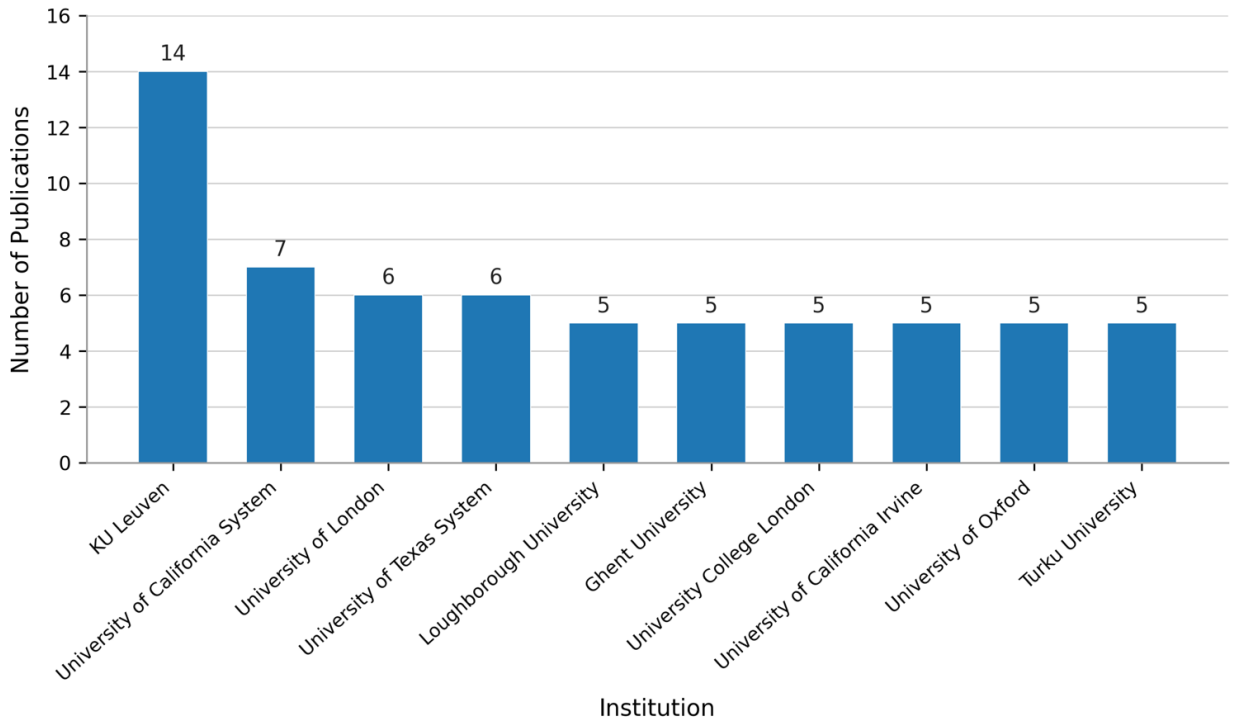

Figure 7. Institutions where publications focused on mathematical development during the preschool period were published - Top 10 institutions (WoS, July 2025) (Source: Authors' own elaboration)

KU Leuven's leadership in output is attributable to the sustained, collaborative productivity of the Verschaffel-Torbeyns-De Smedt research group, which has built a coherent, cumulative research program integrating mathematical cognition, developmental psychology, and educational intervention. This group exemplifies how institutional concentration of expertise—combined with sustained funding and a shared theoretical framework—can generate disproportionate research output. However, the concentration of nearly half the literature within ten institutions raises questions about disciplinary diversity: when a field's knowledge base is produced predominantly by a small number of research centers, the theoretical frameworks, methodological approaches, and population samples that dominate the literature are likely to reflect those centers' particular intellectual traditions and local contexts rather than the full range of global perspectives.

Citation analysis of institutions

Citation analysis was conducted on 44 institutions with the highest link strength and mutual relationships, yielding 10 clusters, 115 links, and 131 total link strength (**Figure 8**). The University of Nebraska leads with 1,570 citations, followed by the University of Aberdeen (1,118) and University College London (526).

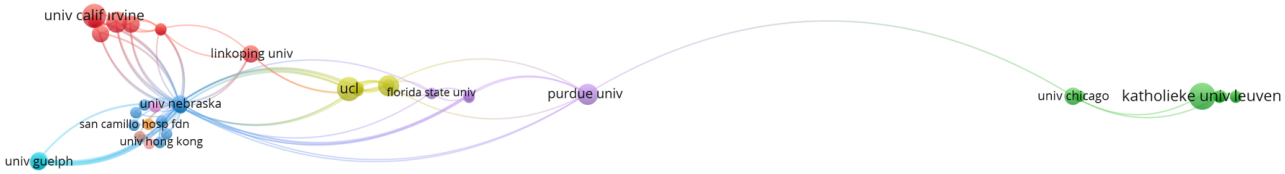

Figure 8. Citation analysis of institutions (WoS, July 2025) (Source: Authors' own elaboration, using VOSviewer)

The divergence between institutional productivity (KU Leuven leads) and citation impact (University of Nebraska leads) extends the author- and country-level finding into the institutional domain and points to a consistent structural pattern: in this field, the most influential contributions do not originate from the most productive institutions. The University of Nebraska's citation primacy is rooted in pioneering studies on executive functions and school readiness—a line of inquiry that established a productive theoretical paradigm that subsequent researchers worldwide adopted and built upon. The University of Aberdeen's second-place citation ranking, driven by Bull et al.'s (2008) study, similarly reflects the paradigmatic rather than programmatic basis of citation impact. These findings are consistent with bibliometric research in education, which shows that institutions with high citation impact tend to be associated with theoretically generative or methodologically innovative research programs rather than with high publication volume alone (Göktepe Yıldız & Göktepe Körpeoğlu, 2025; Irawan et al., 2024; Maharani, 2023).

Co-Authorship Analysis

Co-authorship analysis revealed a central network of 16 authors who form a complete collaboration structure, with 120 total links and 15 links per author (**Figure 9**). This pattern indicates that this group conducts systematic and intensive joint research, functioning as a cohesive research consortium.

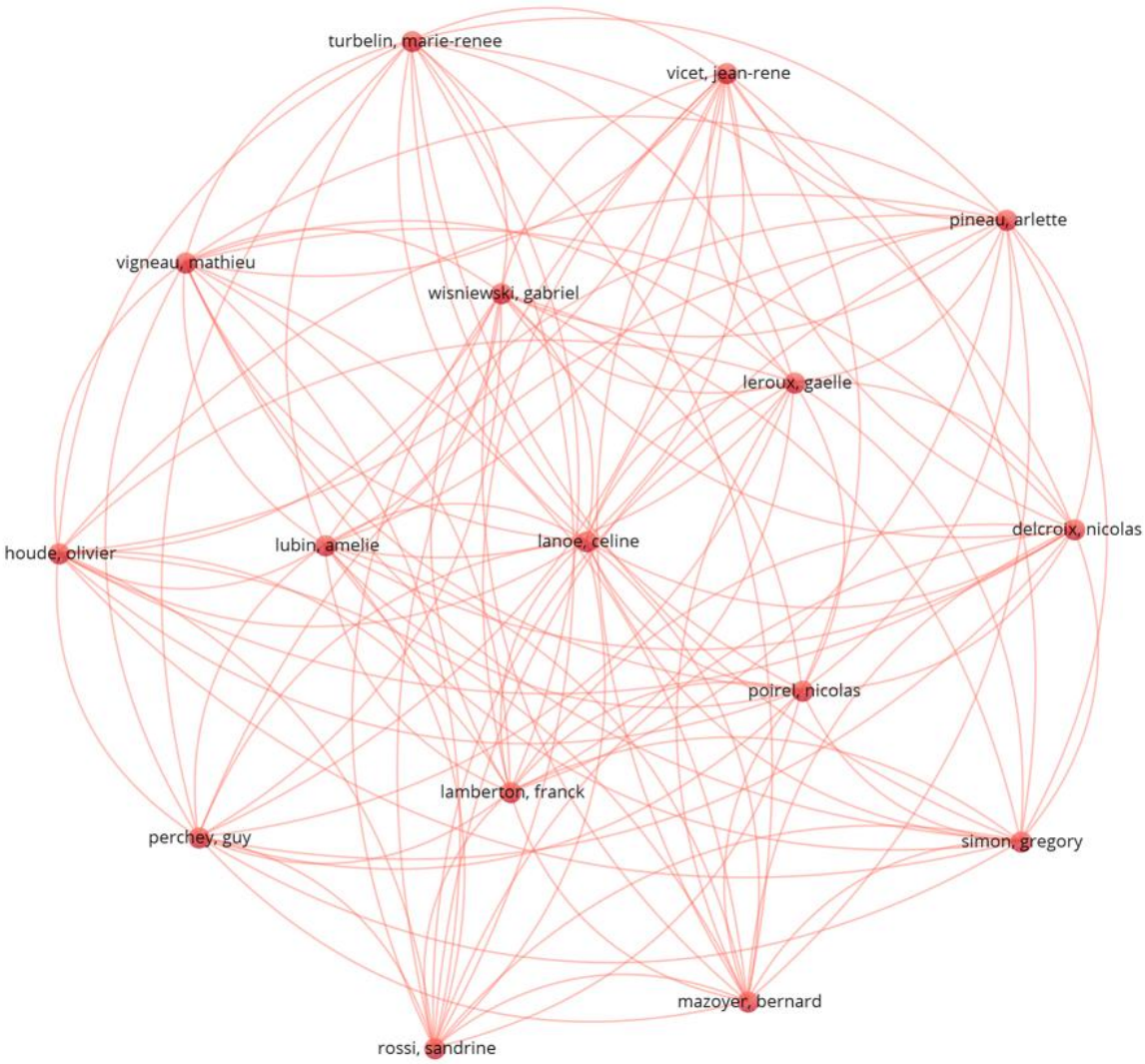

Figure 9. Co-author networks showing collaboration among authors (WoS, July 2025) (Source: Authors' own elaboration, using VOSviewer)

The structural significance of this finding lies not simply in the density of the collaboration network but in its relationship to citation impact. The most highly cited authors—Bull, Espy, and Wiebe—are not embedded in this dense collaboration cluster; they achieved their influential contributions through relatively small, focused research partnerships. This observation reveals two structurally distinct pathways to academic influence in this field. The first is an institutional-collaborative strategy: sustained joint research within a large, well-organized research group, which generates high publication volume, methodological breadth, and cross-site replication capacity. The second is an independent-originality strategy: theoretically ambitious, methodologically rigorous studies produced by small teams that generate high citation impact through paradigmatic rather than programmatic contributions. These two strategies are not mutually exclusive, but their differential presence in this field—and the fact that the second strategy appears to generate greater citation impact than the first—has important implications for how early-career researchers and research funding agencies should think about the relationship between collaboration structure and scholarly influence. This finding extends previous research on the complex, non-linear relationship between network centrality and academic impact (Yan & Ding, 2012) by demonstrating that in developmental education research, peripheral positioning within collaboration networks is not necessarily a disadvantage when it is associated with theoretical originality.

Most Influential Scientific Publications

Citation analysis identified 46 publications meeting the minimum threshold of 20 citations (See **Table 1**). The most cited publication is Bull et al.'s (2008) longitudinal study on executive functioning and preschool mathematics achievement, which has accumulated 1,118 citations—placing it distinctly ahead of all other publications in the field.

Table 1. Most influential publications in the corpus

Rank	Authors	Article Title	Citation Count	Year
1	Bull et al.	Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years	1118	2008
2	Clark et al.	Preschool executive functioning abilities predict early mathematics achievement	453	2010
3	Gilmore et al.	Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement	347	2013
4	Starkey et al.	Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention	342	2004
5	Krajewski and Schneider	Early development of quantity to number-word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study	268	2009
6	Cortés Pascual et al.	The relationship between executive functions and academic performance in primary education: Review and meta-analysis	267	2019
7	Baggetta and Alexander	Conceptualization and operationalization of executive function	251	2016
8	Gunderson and Levine	Some types of parent number talk count more than others: relations between parents' input and children's cardinal-number knowledge	233	2011
9	Purpura and Ganley	Working memory and language: Skill-specific or domain-general relations to mathematics?	137	2014
10	DeFlorio and Beliakoff	Socioeconomic status and preschoolers' mathematical knowledge: The contribution of home activities and parent beliefs	134	2015

Thematic analysis of the top 10 most cited publications reveals a strong, theoretically meaningful focus on executive functions and memory processes: six of the top-ranked studies directly examine the role of cognitive mechanisms—working memory, inhibitory control, and attentional flexibility—in early mathematical achievement. This concentration reflects a paradigmatic commitment within developmental and cognitive psychology to understanding early mathematical competence through the lens of domain-general cognitive resources rather than domain-specific numerical knowledge. The theoretical significance of this commitment is substantial: if domain-general executive resources primarily constrain early mathematical competence, then interventions targeting those resources—rather than or in addition to mathematical content—may be more effective levers for improving outcomes. The remaining four most-cited publications address early intervention programs (Starkey et al., 2004), number concept development (Gunderson & Levine, 2011; Krajewski & Schneider, 2009), and environmental factors such as family support and socioeconomic status (DeFlorio & Beliakoff, 2015)—a theme whose importance has long been recognized in early childhood education programs (Yazar et al., 2010). Their presence among the field's most influential works signals that the literature has not collapsed into a single theoretical framework; instead, it maintains a genuinely multidimensional character that acknowledges the interplay of cognitive, pedagogical, and environmental determinants of early mathematical competence. The temporal clustering of eight of the top 10 most-cited publications between 2008 and 2017 indicates that this period constitutes the formative phase in which the field's conceptual foundations were established. The comparatively lower citation counts of post-2019 publications reflect citation lag rather than lower quality: recently published work has not yet had sufficient time to accumulate influence.

Keyword Analysis

Keyword co-occurrence analysis identified 15 thematic clusters in the preschool mathematical development literature (**Figure 10**).

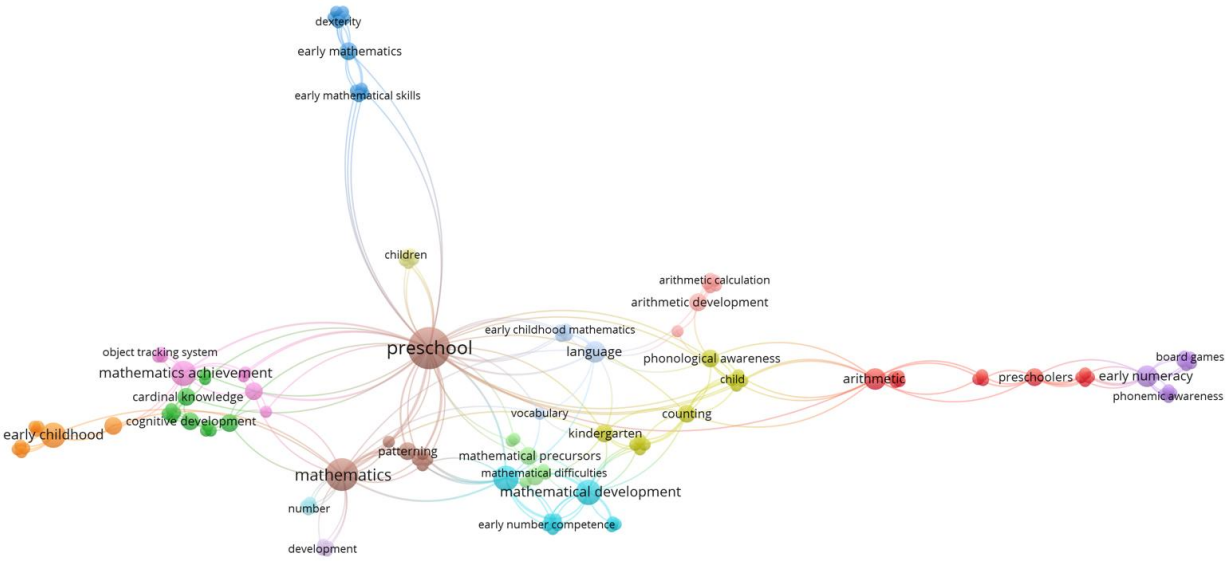

Figure 10. Most frequently used keyword connections (WoS, July 2025) (Source: Authors' own elaboration, using VOSviewer)

The keywords with the highest link strength are 'preschool,' 'mathematics,' 'mathematical development,' 'mathematical achievement,' and 'early childhood' (see **Table 2**). These clusters converge around five major thematic orientations: (1) cognitive processes—particularly executive functions, working memory, attention, and inhibitory control; (2) basic mathematical skills—including number sense, counting, cardinality, and numeracy; (3) instruction and intervention—encompassing school readiness, instructional methods, and intervention programs; (4) environmental and social factors—including parent involvement, home learning environments, socioeconomic status, and family–school partnerships; and (5) developmental and individual differences—including learning difficulties and dyscalculia.

Table 2. Most frequently used keywords with highest link strength

Rank	Keyword	Frequency (f)	Link Strength (ls)
1	Preschool	11	52
2	Mathematics	8	29
3	Mathematical development	7	25
4	Mathematical achievement	5	17
5	Early childhood	4	11

The centrality of 'executive functions' and 'working memory' in the keyword network reflects and reinforces the citation-level finding: the field's dominant theoretical framework is cognitive developmental, and its most productive research tradition links domain-general regulatory processes to early numerical competence. This concentration has been scientifically productive—generating a cumulative, replicable body of findings—but it has also created systematic blind spots. The low frequency of keywords associated with digital tools, STEAM integration, play-based learning, and cross-cultural approaches is not merely a topical gap; it signals a disconnect between the field's dominant research paradigm and the realities of contemporary early childhood educational practice. The field's theoretical models have been developed and validated primarily in controlled, researcher-designed contexts; they have not yet been systematically tested in the technologically enriched, culturally diverse, play-based environments that characterize early childhood education in much of the world. This gap between the epistemological commitments of the research community and the ecological validity of its findings arguably represents the most consequential limitation of the current literature.

Temporal change analysis

Overlay visualization in VOSviewer reveals a clear temporal evolution in thematic emphases. During 2006–2012, research predominantly focused on foundational mathematical skills such as number sense, counting, and numeracy. Between 2013 and 2018, cognitive processes—particularly executive functions and working memory—became dominant. In the most recent period (2019–2025), there has been a noticeable shift toward holistic, interdisciplinary approaches, including STEAM education, digital tools, and parent involvement. This three-phase temporal arc has an important theoretical interpretation. The first phase (basic skills documentation) established the empirical existence and developmental significance of early mathematical competencies. The second phase (cognitive mechanisms) provided a theoretical explanation for why these competencies predict long-term outcomes by situating them within a broader cognitive developmental architecture. The third phase (interdisciplinary integration) reflects an emerging recognition that the cognitive developmental framework, while powerful, is incomplete: it must be extended to accommodate the cultural, technological, and pedagogical contexts in which early mathematical development actually occurs. Whether this third-phase shift constitutes a durable paradigmatic extension or a transient methodological trend will be an important question for future bibliometric analyses.

CONCLUSION AND DISCUSSION

This study employed bibliometric analysis to map 143 academic publications on preschool mathematical development published between 2006 and 2025. The findings, taken together, tell a coherent story about a field that has matured rapidly, established a dominant theoretical framework, and generated a substantial empirical base—but that also exhibits structural imbalances and theoretical blind spots that constrain its future development. Four overarching conclusions emerge from the analysis.

The first and most theoretically significant conclusion is the consistent dissociation between productivity and citation impact observed at the author, country, and institutional levels. The most prolific authors, countries, and institutions are systematically different from the most influential ones. This pattern suggests that the field's intellectual agenda has been set by paradigm-defining contributions—a small number of theoretically ambitious, methodologically rigorous studies that opened new research territories—rather than by sustained programmatic output. Bull et al.'s (2008) study is the clearest example: a single longitudinal investigation that repositioned early mathematical development within a cognitive developmental framework generated more citations than the combined output of the field's most prolific research group. This finding has direct implications for how scholarly contributions should be evaluated in this field: citation impact, rather than publication volume, is the more meaningful indicator of intellectual influence, and it is generated primarily by theoretical originality and methodological rigor rather than by collaborative scale or institutional resources.

The second conclusion concerns the field's geographic structure. The concentration of research output in North America and Western Europe—with seven of the ten most productive countries located in North America or Europe—is not merely a bibliometric artifact. It reflects a fundamental epistemological limitation: the field's theoretical models, assessment tools, and intervention designs have been developed and validated within a restricted range of cultural, linguistic, and socioeconomic contexts. This matters because preschool mathematical development is not a culturally neutral process. The structure of number language,

cultural practices around counting, and the social value placed on formal mathematical knowledge vary substantially across cultures and influence early mathematical competence in ways that Western-centric models may not adequately capture (Clements & Sarama, 2009). The field's growing reliance on cognitive developmental frameworks derived predominantly from WEIRD (Western, Educated, Industrialized, Rich, Democratic) samples raises legitimate questions about the generalizability of its central findings—questions that cannot be answered within the current geographic boundaries of the literature. These findings are consistent with global patterns of inequality in scientific production (King, 2004; Moral-Muñoz et al., 2020), but they acquire particular urgency in a field whose subject matter is inherently cultural.

The third conclusion concerns the field's thematic structure. Citation and keyword analyses confirm that executive functions and cognitive processes occupy a dominant position in the field's conceptual architecture. Six of the top 10 most influential publications directly address executive functions, memory, or attentional processes, and the keyword network is organized around cognitive developmental themes. This concentration has been scientifically productive, generating a cumulative and replicable body of findings linking domain-general cognitive skills to early mathematical achievement (Blair & Razza, 2007; Clements & Sarama, 2009; Fuchs et al., 2010). However, the simultaneous underrepresentation of digital technologies, play-based learning, STEAM integration, and cross-cultural perspectives reveals a systematic mismatch between the field's dominant theoretical framework and the pedagogical realities of contemporary early childhood education. The field's conceptual foundations, established primarily during 2008–2017, reflect the theoretical priorities of that era; the challenge now is to extend those foundations to encompass the technologically enriched, culturally diverse, and play-oriented environments in which preschool mathematics is actually taught and learned. The presence among the most influential publications of intervention studies (Starkey et al., 2004), environmental factor research (DeFlorio & Beliakoff, 2015), and number concept development work (Gunderson & Levine, 2011; Krajewski & Schneider, 2009) demonstrates that the field has never been purely cognitive-reductionist; the multidimensional character of its foundational literature provides a basis for the theoretical expansion that the current gaps demand.

The fourth conclusion concerns the field's temporal trajectory. The three-phase evolution documented in the keyword overlay analysis—from basic skills (2006–2012) to cognitive mechanisms (2013–2018) to interdisciplinary integration (2019–2025)—mirrors the broader intellectual development of the cognitive and educational sciences. The emergence of STEAM frameworks, digital tools, and parent involvement themes in the most recent period suggests that the field is beginning to move beyond its cognitive-developmental paradigm toward a more contextually embedded and ecologically valid understanding of preschool mathematical development. These findings are consistent with bibliometric studies documenting increased publication volumes and thematic diversification in early childhood education research after 2010 (Çelik, 2022; İdil & Yıldırım, 2025; Moral-Muñoz et al., 2020). Whether this third-phase shift represents a durable paradigmatic transformation or a transient diversification remains to be determined, but it clearly identifies the frontier of the field's current development.

THEORETICAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

This study makes five distinct theoretical contributions that advance the field beyond what descriptive bibliometric mapping alone can offer. First, it provides a comprehensive bibliometric map of preschool mathematical development as a theoretically distinct construct—rather than a subcategory of preschool education more broadly—across a 20-year horizon. By focusing specifically on mathematical development, the analysis captures the cognitive, neuroscientific, and longitudinal dimensions of the field that broader educational bibliometric analyses typically subsume under broader thematic categories.

Second, the consistent dissociation between productivity and citation impact at the author, country, and institutional levels constitutes a theoretically novel finding about the dynamics of knowledge production in developmental education research. This dissociation suggests that the field operates according to a paradigm-driven rather than output-driven logic of influence—a conclusion with implications for how the sociology of science literature (Kuhn, 1970) applies to applied developmental research fields.

Third, the identification of 15 thematic clusters and five major research foci provides a granular structural representation of the field's intellectual architecture, serving as a framework for future theory-building and research design. By making visible the thematic distances and proximities between research clusters, the keyword network map enables researchers to identify not only what is studied but what is conspicuously not studied, thereby generating theoretically grounded research questions rather than merely inventorying existing knowledge.

Fourth, the three-phase temporal evolution documented in the overlay analysis—basic skills, cognitive mechanisms, and interdisciplinary integration—can be interpreted as a theory of the field's development that has both predictive and descriptive value. If the pattern continues, the coming decade should be characterized by increasing integration of cognitive developmental findings with technological, cultural, and pedagogical frameworks. This prediction provides a theoretically grounded basis for anticipating the field's most productive future research territories.

Fifth, the explicit identification and theoretical interpretation of research gaps—particularly in cross-cultural research, digital tool integration, and play-based learning—provides an evidence-based foundation for theoretical extension. These are not merely missing topics; they represent domains in which the field's dominant cognitive developmental framework has not yet been tested under ecologically valid conditions, and where its predictions may need revision.

Beyond theoretical contributions, the study offers practical value for multiple stakeholders. It provides an evidence-based roadmap for researchers—particularly early-career scholars—by identifying influential authors, institutions, seminal publications, and emerging topics. The findings inform education policymakers by clarifying the scientific foundations of early childhood

mathematics education and identifying areas requiring strategic investment. For teacher educators, the results highlight dominant conceptual emphases and contemporary research insights relevant to preschool teacher preparation and professional development.

Future research priorities directly derived from the identified gaps include: (1) cross-cultural and comparative studies examining preschool mathematical development across diverse linguistic, cultural, and socioeconomic contexts, with particular attention to non-WEIRD populations; (2) studies integrating digital technologies—including apps, tablets, and adaptive learning systems—within cognitive developmental and intervention frameworks; (3) research on STEAM-integrated approaches examining the joint development of mathematical, scientific, and creative competencies in early childhood; (4) longitudinal studies on the role of play-based learning in supporting mathematical development, particularly given increasing formalization pressure in early childhood settings; and (5) studies on teacher professional development specifically targeting preschool educators' mathematical content knowledge and pedagogical content knowledge. These priorities are aligned with the temporal trajectory of emerging themes in the literature and are therefore evidence-based rather than speculative.

RECOMMENDATIONS

For researchers: future bibliometric analyses of this field should integrate multiple databases—including Scopus, ERIC, and Google Scholar—to address the systematic WoS coverage bias documented in this study and capture a more representative body of literature, particularly from non-English-language and non-Western sources. Complementing bibliometric analyses with systematic reviews or meta-analyses would strengthen interpretive depth by enabling causal claims about thematic trends that descriptive bibliometric mapping cannot support. Longitudinal social network analyses tracking co-authorship and citation patterns over time would illuminate the dynamics of knowledge production and intellectual influence in ways that cross-sectional snapshots cannot. Given the identified theoretical blind spots, future empirical research should deliberately prioritize cross-cultural designs, digital tool integration, and play-based learning contexts—not merely as new topical additions but as systematic tests of whether the field's cognitive developmental frameworks generalize beyond the Western, laboratory-based, content-focused contexts in which they were developed.

For practitioners and policymakers: the dominance of cognitive developmental findings—particularly regarding executive functions and working memory—suggests that early childhood mathematics programs should explicitly incorporate activities designed to support cognitive self-regulation alongside numerical skill development. The emerging evidence on digital tool integration and parent involvement supports investment in technology-assisted home learning programs as complementary to formal preschool mathematics instruction. The identified underrepresentation of developing countries in the research base suggests the need for internationally funded research initiatives that build research capacity in these regions, both to test the generalizability of existing findings and to generate locally relevant evidence for educational policy. Policymakers in non-Western contexts should be cautious about directly importing intervention models developed in Western settings without cultural adaptation and local validity testing.

LIMITATIONS

Several methodological limitations of this study warrant transparent and critical discussion. The most consequential is the restriction to WoS as the sole database. WoS has historically favored English-language, Western journals; its coverage of education research from developing regions, non-English-language publishing traditions, and emerging open-access venues is systematically incomplete. This means that the geographic concentration of research output documented in the findings—the near-absence of contributions from Sub-Saharan Africa, Southeast Asia, and Latin America—may be partly an artifact of database selection rather than an accurate reflection of global research activity. Future studies should address this by employing multi-database searches across WoS, Scopus, ERIC, and Google Scholar, explicitly comparing results across databases, and reporting discrepancies as substantive findings rather than methodological footnotes.

The keyword strategy in the search string introduces a second boundary condition: studies that address preschool mathematical development but do not use the specific terms may have been missed. This is a known limitation of keyword-based bibliometric searches. The use of both author keywords and Keywords Plus partially mitigates this limitation—Keywords Plus captures thematic content not always reflected in author-assigned terms—but it cannot fully compensate for semantic variation in how researchers describe their work across different national and disciplinary traditions. The 143 publications analyzed, therefore, constitute a systematic but not exhaustive representation of the field.

Citation-based analyses are subject to citation lag: the impact of recently published studies (post-2019) is systematically underestimated relative to earlier publications simply because less time has elapsed for citations to accumulate. This temporal bias should be borne in mind when interpreting the concentration of highly cited publications in the 2008–2017 period; it does not necessarily reflect a genuine decline in research quality or theoretical ambition in the most recent period. Additionally, citation counts measure academic visibility and uptake rather than intrinsic quality or correctness; highly cited publications are not necessarily the most methodologically rigorous, and uncited publications are not necessarily without merit. The bibliometric findings should therefore be interpreted as indicators of academic influence within the field's current knowledge production system—a system that, in turn, reflects the inequalities and paradigmatic commitments documented in this analysis.

Finally, data collection was completed in July 2025; the 2025 publication counts, therefore, represent only a partial year and will be revised upward by year-end. Researchers replicating or extending this analysis should re-run the search to capture the complete 2025 cohort and update the temporal trend analysis accordingly.

Author contributions: FHİ: conceptualization, study design, data curation, bibliometric analysis, writing – original draft; **SYİ:** conceptualization, supervision, formal analysis, writing – review & editing. Both authors reviewed and approved the final version of the manuscript.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study used publicly available bibliographic data and did not involve direct interaction with human participants or the collection of personal data. Formal ethical approval was not required. All citations and bibliographic information were used in accordance with academic integrity principles.

AI statement: The authors stated that no Generative AI or AI-based tools were used in the data analysis or the preparation of this manuscript.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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