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Review Article

Flipped Classroom in University-Level Mathematics: A Decade of Research Trends and Impact

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ABSTRACT

This bibliometric analysis investigates the adoption and development of the flipped classroom approach in university mathematics education using 165 Scopus-indexed journal articles published between 2014 and 2024. The research, conducted using Biblioshiny in R, examines publication trends, key contributors, and thematic patterns via co-citation networks and keyword mapping. Results demonstrate a steady increase in research output, particularly subsequent to 2020, driven by the shift toward blended and online learning. Dominant themes include student engagement, digital learning tools, and curriculum design, with an emerging emphasis on artificial intelligence and adaptive learning technologies. Citation analysis identifies foundational studies but highlights critical research gaps, including the need for standardized assessment frameworks, evaluation of long-term learning outcomes, and broader implementation across diverse mathematical subfields. This study provides a structured overview of the field and identifies directions for future inquiry, supporting educators and policymakers in advancing evidence-based teaching strategies in university-level Mathematics.

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1. INTRODUCTION

The flipped classroom has become an important instructional approach in twenty-first century education. By shifting direct instruction to pre-class activities such as videos, readings, or interactive resources, class time can be used for guided discussion and problem-solving (Azizan and Liau, 2024). Implementation varies across disciplines. In STEM fields, students review procedural content before class and apply it during structured in-class work (Jensen et al., 2018). In the humanities, pre-class preparation often centres on text analysis, followed by seminar-style dialogue (Hantla, 2018). This structure enables students to work collaboratively and benefit from more purposeful interaction with instructors. Studies in mathematics report improved in-class participation and better development of reasoning skills (Lo and Hew, 2021; Nouri, 2016). Supportive instructor feedback further contributes to positive learning outcomes (Chen et al., 2023).

These disciplinary contrasts highlight the importance of aligning flipped instruction with the nature of the subject. University mathematics presents distinct challenges due to its abstract content. In medical education, flipped models often combine video lectures with simulations or case-based diagnostics (Mishall et al., 2024), whereas mathematics courses rely more on structured group work and facilitated problem analysis (Al-Samarraie et al., 2020). The flipped approach encourages students to arrive with initial exposure to key ideas, allowing class time to focus on deeper understanding (Sun et al., 2018). This model helps students take responsibility for preparation and gradually build confidence in managing challenging topics (Baig and Yadegaridehkordi, 2023). Digital tools also support comprehension of difficult concepts and sustain motivation (Nadarajan et al., 2023). While its value is recognised in school mathematics (Egara and Mosimege, 2024a, 2024b), the model is especially helpful in university settings where abstraction often becomes a barrier (Schleppegrell, 2007). Aligning pre-class preparation with in-class consolidation supports stronger conceptual understanding consistent with constructivist learning principles (Erbil, 2020).

In higher education, the growing complexity of mathematical content calls for instruction that supports both conceptual clarity and independent preparation (Yorganci, 2020). Flipped lessons allow class meetings to be used for targeted practice that strengthens understanding and fosters a sense of academic community (Yohannes and Chen, 2024). Research has reported gains in achievement and attitudes toward mathematics when flipped models are adopted (Spotts and de Blume, 2020; Strelan et al., 2020a, 2020b). The approach encourages responsibility for learning and promotes productive interaction with instructors and peers (Urquiza-Fuentes, 2020). Its grounding in constructivist and social-constructivist theories reflects the view that learning is strengthened by active participation and timely guidance (Gok and Bozoglan, 2016). Despite its strengths, the model faces practical challenges. Limited in-class time may disadvantage students who need more opportunities to work through complex ideas (Mazana et al., 2024). Unequal access to technology can limit engagement with pre-class materials (Singh et al., 2022). Large classes may reduce opportunities for meaningful collaboration, and readiness for independent preparation varies widely (Shnai, 2017). Early implementation often results in only modest improvements in motivation and performance (Setren et al., 2021). Educators also face demands related to preparing digital materials, managing online platforms, and facilitating in-class activities (Martinez-Jimenez and Ruiz-Jimenez, 2020). Resistance to change, from both students accustomed to traditional lectures and instructors concerned about workload, remains a challenge (Buhl-Wiggers et al., 2023).

Understanding how flipped classrooms have been studied, where they have been implemented, and what outcomes they produce is important for improving research and practice. Bibliometric analysis provides a systematic method for examining influential studies, collaborative patterns, and thematic developments. Existing bibliometric studies have examined flipped classrooms in general education contexts. Sihotang et al. (2023) identified consistent growth in mathematics-related publications from 2016 to 2021. Del Arco et al. (2022) highlighted broad research directions, while Soebagyo and Saamah (2023) identified opportunities for future work. However, these studies focus mainly on school or general education settings. A dedicated review of flipped classroom research in university mathematics is still lacking.

This study addresses that gap by pursuing three aims: (i) to analyse research trends and thematic patterns in flipped classroom studies within university mathematics, (ii) to identify influential authors, institutions, and journals that shape developments in this field, and (iii) to examine citation and co-citation patterns that reveal the intellectual foundations of the research area.citation and co-citation patterns that reveal the intellectual foundations of the research area. Together, these objectives provide a comprehensive overview of how flipped classroom research has developed over the past decade in university mathematics. The analysis highlights long-term patterns, major contributors, and emerging themes, offering insights for educators, researchers, and policymakers seeking to strengthen evidence-informed teaching in higher education.

2. METHODOLOGY

2.1. Scope of the Research

The bibliometric research method is a well-established approach for mapping relationships among disciplines, research fields, scholars, and individual publications (Zupic & Čater, 2014). Its increasing prominence stems from its ability to systematically organize and visualize the structure of scientific domains, thereby clarifying research trends, collaboration networks, and intellectual connections (Boyack & Klavans, 2014). This study employs bibliometric analysis due to its effectiveness in quantifying research impact, tracking collaboration patterns, and identifying thematic shifts over time. While systematic literature reviews provide qualitative insights into theoretical frameworks, bibliometric analysis complements this by offering data-driven assessments of research productivity, co-authorship dynamics, and citation influence. This approach is particularly suited to investigating the evolution of flipped classroom research in university-level mathematics over the past decade, as it leverages large-scale scientometric data to systematically identify patterns and key contributions. Specifically, this study applies bibliometric techniques to analyse publications on flipped classrooms in university mathematics education. To ensure methodological rigour, the document selection process adhered to the PRISMA guidelines (Page et al., 2021), with a detailed protocol outlined in Table 1.

Table 1. Search Protocol

Aspect	Description
Study Period	2014-2024
Access Date	20 January 2025
Database	Scopus
Keyword search string	((``flipped classroom'' OR ``flipped learning'' OR ``inverted classroom'' OR ``flipped instruction'' OR ``flipped teaching'' OR ``reverse classroom'' OR ``flipped pedagogy'') AND (``university mathematics'' OR ``college mathematics'' OR ``higher education mathematics'' OR ``tertiary mathematics'' OR ``undergraduate mathematics'' OR ``graduate mathematics'' OR ``mathematical sciences'' OR ``calculus'' OR ``abstract algebra'' OR ``linear algebra'' OR ``differential equations'' OR ``discrete mathematics'' OR ``probability'' OR ``statistics'' OR ``numerical methods'' OR ``numerical analysis'' OR ``topology'' OR ``complex analysis'' OR ``real analysis'' OR ``mathematical logic'' OR ``mathematical modelling'' OR ``differential geometry'' OR ``game theory'' OR ``functional analysis'' OR ``operations research'' OR ``set theory'' OR ``combinatorics'' OR ``applied mathematics'' OR ``number theory'' OR ``graph theory'' OR ``multivariable calculus''))
Inclusion Criteria	**Subject Area**: Mathematics, Computer Science, Engineering, Decision Sciences, Energy, Economics, Econometrics, Finance, Physics, Astronomy **Document Type**: Article **Language**: English **Source Type**: Journal **Publication Stage**: Final

2.2. Search Protocol

The search protocol for this study was meticulously designed to ensure a comprehensive and precise bibliometric analysis. The study period, spanning from 2014 to 2024, captures the decade in which flipped classroom pedagogy has gained significant momentum in educational research. By covering both the early adoption of flipped classroom techniques and the most recent developments, this timeframe enables the identification of long-term trends and emerging themes in the research field. Scopus was selected as the primary database because of its extensive coverage of interdisciplinary research and its high-quality journal indexing in education, mathematics, and related disciplines. Although Web of Science is also a reputable database, Scopus offers broader coverage of social sciences and education literature, which makes it more suitable for this study. PubMed, which focuses primarily on biomedical research, was considered less relevant. Scopus is also well known for its advanced tools that support the tracking, analysis, and visualization of research outputs, helping to ensure a reliable dataset for bibliometric analysis. The keyword search string was carefully constructed to include relevant literature on flipped classrooms in the context of university-level mathematics. To account for variations in terminology across studies, the search included terms such as "flipped classroom," "flipped learning," "inverted classroom," and "reverse classroom." Specific mathematical disciplines such as "calculus," "linear algebra," "probability," and "numerical analysis'" were also included to reflect the diverse applications of flipped pedagogy in university-level. Boolean operators (AND, OR) and wildcards were used to enhance search precision while balancing inclusivity and relevance. To further refine the dataset, inclusion criteria focused on high-quality, peer-reviewed research. The selected subject areas include Mathematics, Computer Science, Engineering, Decision Sciences, Energy, Economics, Finance, Physics, and Astronomy, allowing the study to capture interdisciplinary applications while maintaining a core emphasis on university-level mathematics. The search was limited to journal articles to ensure the inclusion of rigorously reviewed and impactful studies. Restricting the selection to English-language publications further enhances accessibility and consistency in analysis. Finally, preliminary or incomplete publications were excluded to preserve the reliability of the dataset.

2.3. Data Analysis

Bibliometric analysis was conducted using the Biblioshiny package from R-Studio, a widely used tool for bibliometric and scientometric studies. This package provides a comprehensive suite of functions for analysing and visualizing bibliometric data, making it an ideal choice for this study. The analysis focused on several key aspects to ensure a thorough examination of the research landscape. Table 2 presents the research objectives, the corresponding strategies employed to address each research question, and the bibliometric methods used in data analysis.

Table 2. Summary of research questions, strategies, and results used

RO	Description	Strategy to Answer RQ	Results Used
1	To analyse research trends and thematic patterns in flipped classroom studies within university-level mathematics.	Examine annual publication trends, keyword co-occurrence networks, and thematic evolution to identify dominant themes and emerging research directions.	Annual Scientific Production, Keyword Co-Occurrence, Thematic Evolution, Word Cloud
2	To identify influential contributors, including authors, institutions, and journals, and evaluate their impact on flipped classroom research in mathematics.	Analyse author impact, institutional contributions, and journal relevance using citation metrics, H-index, and collaboration patterns.	Author Impact, Most Relevant Authors, Most Relevant Sources
3	To explore the intellectual structure of the field by examining foundational studies, citation networks, and collaborations.	Analyse citation and co-citation networks to uncover foundational works, research clusters, and collaborations shaping the discourse.	Most Global Cited Documents, Most Local Cited References, Co-Citation Networks, Collaboration Networks

3. RESULTS

The dataset spans the decade from 2014 to 2024, capturing both the early development and recent advancements in flipped classroom research within university-level mathematics. A total of 165 documents were identified, forming a substantial corpus for bibliometric analysis. These publications originate from 75 distinct sources, reflecting a broad range of journals contributing to the discourse on flipped classroom pedagogy in university-level mathematics. The diversity of sources illustrates the interdisciplinary nature of this area, integrating pedagogical innovations with mathematics education at the tertiary level. An annual growth rate of 14.28% indicates a steady rise in scholarly output, despite fluctuations, signalling growing academic interest and recognition of the flipped classroom as a relevant teaching approach in university-level mathematics.

The dataset comprises contributions from 433 authors, indicating robust academic engagement in this research domain. Of the total publications, 36 documents (8.3%) were single-authored, suggesting that a subset of scholars conducts independent research, potentially addressing specialized or foundational aspects of the flipped classroom methodology. Collaboration is a prominent characteristic, with an average of 2.81 co-authors per document, reflecting a tendency toward small, interdisciplinary research teams that combine expertise in education, mathematics, and instructional design. International collaborations account for 10.91% of publications, indicating a moderate level of global cooperation and opportunities for further cross-border engagement. Analysis of keyword co-occurrence identifies 460 unique author-supplied keywords, which highlights the thematic diversity and multidisciplinary scope of inquiry in this field. Collectively, the documents cite 5,752 distinct works, reflecting the substantial body of literature that informs current research on flipped classrooms in university mathematics education. The average document age of 5.3 years suggests that most contributions are relatively recent, consistent with the growing scholarly interest in flipped classroom pedagogy as an innovative instructional approach over the past decade. The average citation counts of 19.27 per document further underscores the academic significance of this corpus. This metric indicates that the analysed studies have contributed meaningfully to scholarly discourse on pedagogical innovations in university-level mathematics education. Collectively, these findings constitute a robust dataset, offering a comprehensive understanding of the field's intellectual impact, collaborative dynamics, and thematic evolution. The search yielded the data visualized in Figure 1.

Figure 1. Main Information

3.1. Annual Scientific Production

Building on the dataset analysis, Figure 2 presents the annual publication trends for flipped classroom research in university-level mathematics from 2014 to 2024. Examining these trends helps illustrate how scholarly attention toward this pedagogical model has evolved over the past decade. The chart shows fluctuations in research output, reflecting shifts in academic interest. The trend begins modestly in 2014, with fewer than 10 articles published. A notable surge occurred in 2015, with output exceeding 20 publications, marking an early peak in research activity. However, this momentum was short-lived, as the number of publications dropped sharply in 2016, falling below 10. Between 2016 and 2018, research output remained inconsistent, with minor fluctuations, suggesting sporadic engagement with the topic during this period.

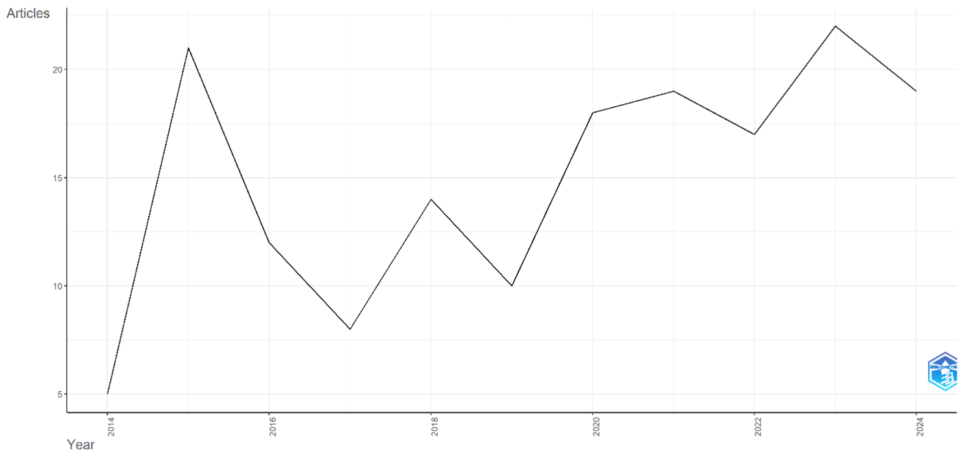

Figure 2. Annual Scientific Production

From 2019 onward, a steady upward trend is evident, peaking in 2023 with over 20 publications. The publication pattern shows phases of growth, occasional declines, and renewed interest, particularly in response to global educational challenges during the COVID-19 pandemic (Collado-Valero et al., 2021). In 2024, a slight decrease is observed, possibly signalling the end of a research cycle or a shift in academic priorities. Overall, the trend reflects growing scholarly interest in flipped classrooms in university-level mathematics, marked by fluctuations followed by notable growth in recent years. This points to the increasing relevance of this teaching approach in higher education research.

3.2. Keyword Co-Occurrence

Beyond publication trends, an analysis of keyword co-occurrence shows how research themes have developed within the field. The network in Figure 3 visualizes relationships among frequently used keywords, mapping the thematic structure and conceptual focus of flipped classroom studies in university-level mathematics. The network is organized into distinct clusters, each color-coded to represent specific thematic areas within the research landscape.

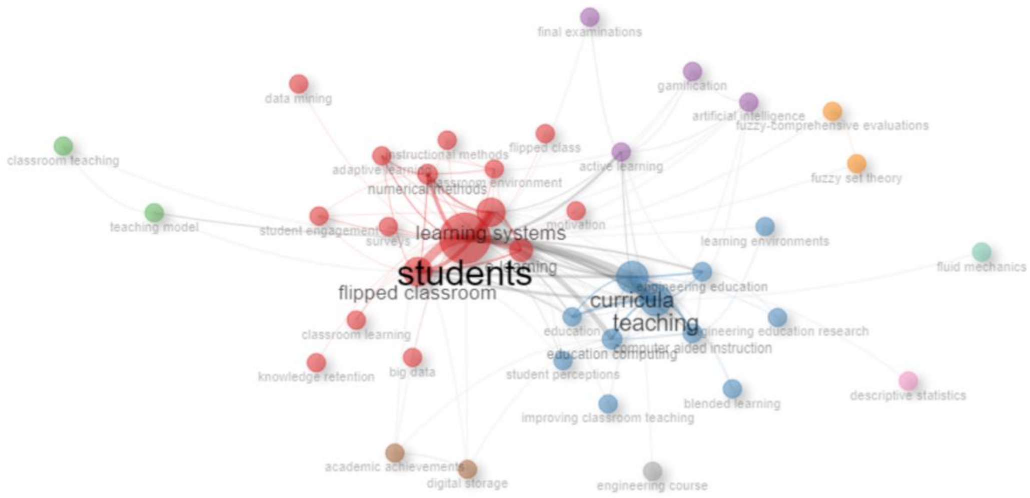

Figure 3. Co-occurrence network

At the heart of the network, the term "students" stands out as the most prominent node, reflecting the strong emphasis on learner-centred approaches in this field. It is closely linked to keywords such as "flipped classroom," "learning systems," and "curricula." This linkage indicates a strong focus on developing and applying pedagogical frameworks to enhance student outcomes. These connections emphasize the role of flipped classroom methodologies in transforming instructional practices to support active student participation. The co-occurrence network presents five major thematic clusters, each representing a key area of research focus. The red cluster centres on student engagement and learning systems. This cluster features terms like "adaptive learning," "numerical methods," and "surveys". This cluster reflects efforts to promote active learning and improve problem-solving skills through interactive and adaptive educational environments. The blue cluster focuses on curriculum design and teaching strategies, with keywords such as "teaching," "curricula," and "blended learning." This group reflects initiatives to reform educational practices. It focuses on integrating innovative teaching methods to achieve better learning outcomes.

The purple cluster focuses on the integration of emerging technologies and innovative digital tools within flipped classroom frameworks. This is indicated by terms such as "gamification," "artificial intelligence," and "fuzzy set theory". This cluster reflects a research emphasis on improving teaching effectiveness through technological advancement. The green cluster represents traditional pedagogical models, with core terms such as "teaching model" and "classroom teaching." This grouping serves as a conceptual comparison point for flipped classroom methods, supporting analyses of different instructional approaches across educational paradigms. Another cluster, identified by the colour orange, addresses evaluative aspects of flipped classrooms and is characterized by terms like "student perceptions" and "fuzzy-comprehensive evaluations." This area systematically examines the effectiveness of flipped methodologies and their impact on learner outcomes and educational experiences. The network reveals strong links among key concepts such as "students," "flipped classroom," and "learning systems," which are central to this field. In contrast, peripheral terms like "data mining" and "digital storage" suggest new or less-studied directions. Overall, the co-occurrence network offers a comprehensive view of the thematic structure of flipped classroom research, mapping both established topics and emerging trends shaping the field's development.

3.3. Thematic Map

While keyword co-occurrence provides insight into frequently discussed concepts, a thematic mapping analysis offers a broader perspective on the structural development of research in this field. Figure 4 illustrates the thematic map of research on flipped classrooms in university-level mathematics, categorizing key themes based on their centrality (relevance) and density (development). The map categorizes themes into four quadrants: Motor Themes, Basic Themes, Niche Themes, and Emerging or Declining Themes, providing insights into which themes dominate the field, and which are emerging or declining.

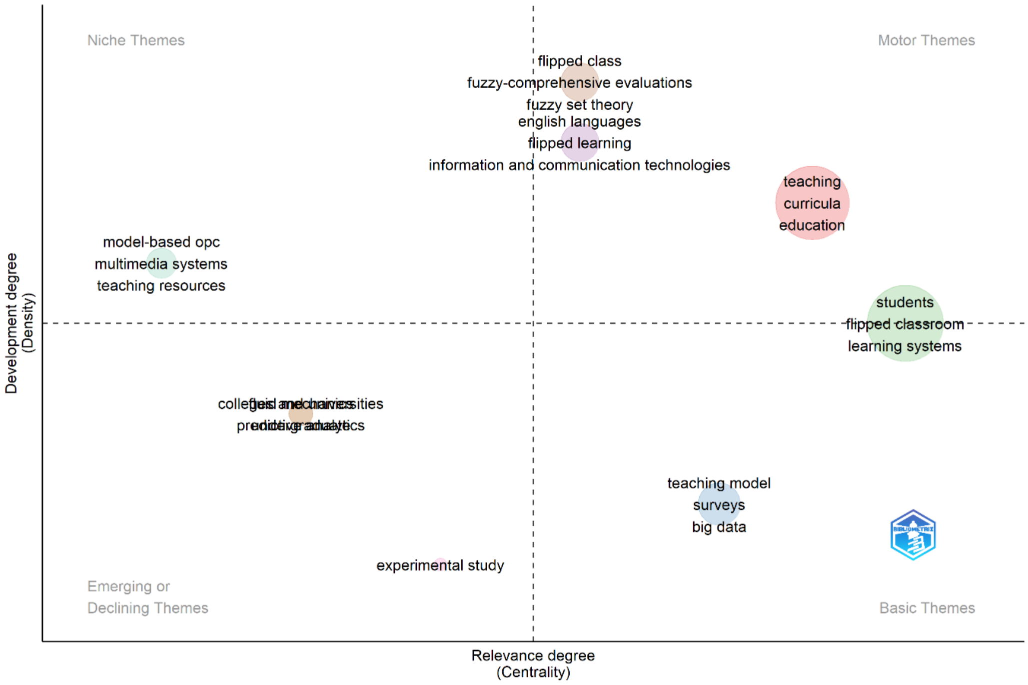

Figure 4. Thematic map

The thematic analysis map categorizes research themes into four distinct clusters, each reflecting varying levels of development and relevance within the field of flipped classroom research. Motor themes, such as "teaching," "curricula," and "education," are central and well-developed, representing the backbone of the discipline. These themes emphasize the field's strong focus on practical applications. This is particularly evident in designing instructional strategies and reforming educational practices to enhance learning outcomes. Their prominence signals the importance of pedagogical innovation and institutional adaptation in the context of flipped classrooms. Basic themes, including "students," "flipped classroom," and "learning systems," form the conceptual foundation of the field. These terms are integral to understanding learner-centred methodologies and the core principles of flipped learning. However, their moderate prominence in the map suggests they are well integrated but not yet exhaustively explored. This points to opportunities for further theoretical refinement and empirical investigation, particularly in areas such as student engagement, adaptive learning systems, and the long-term impacts of flipped classroom models.

Niche themes, such as "model-based OPC," "multimedia systems," and "teaching resources," represent specialized research areas that address specific technical or contextual challenges. Although these themes are well developed, they occupy a less central position in the broader discourse. This reflects their limited generalizability. For instance, studies on multimedia systems or resource optimization often focus on integrating advanced technologies or enhancing instructional materials within flipped learning environments, but their relevance may not extend uniformly across all educational settings. Over time, however, certain niche themes have gained prominence and contributed to the evolving landscape of flipped classroom research. For example, multimedia systems were initially investigated as supplementary tools but have since become integral to content delivery, supporting interactive and student-centred learning environments. Similarly, predictive analytics, once considered an emerging topic, is now increasingly utilized to personalize instruction by enabling educators to tailor content based on student performance data.

While the thematic map provides a static representation, current research trends indicate that digital tools and AI applications are gradually moving from peripheral topics to more central components of flipped learning. As institutions adopt data-driven decision-making and adaptive learning technologies, these themes are likely to become key drivers of pedagogical innovation. Future research may further explore this shift by examining how emerging methodologies influence instructional design and student engagement within flipped classroom settings. Emerging or declining themes, such as ''experimental study,'' "colleges and universities," and "predictive analytics," remain underdeveloped and occupy a marginal position in the current research landscape. These topics may reflect exploratory investigations, methodological developments, or evolving scholarly interests. Their limited prominence highlights gaps in the literature and points to potential directions for future inquiry, including expanding empirical validation, assessing institutional-level implementation, and applying data-driven approaches such as predictive analytics to enhance flipped classroom practices. Overall, the thematic structure suggests that while flipped classroom research continues to emphasize curriculum development and pedagogy, it is increasingly incorporating technology-driven and assessment-oriented dimensions.

3.4. Influential Contributors

3.4.1. Author Impact Analysis

Having established the key research themes, it is essential to examine the scholars driving this discourse. Figure 5 depicts the local impact of authors in the field of flipped classrooms within university-level mathematics, as measured by their H-index. Understanding the contributions of these researchers helps clarify the intellectual structure of the field and the influence of its key contributors.

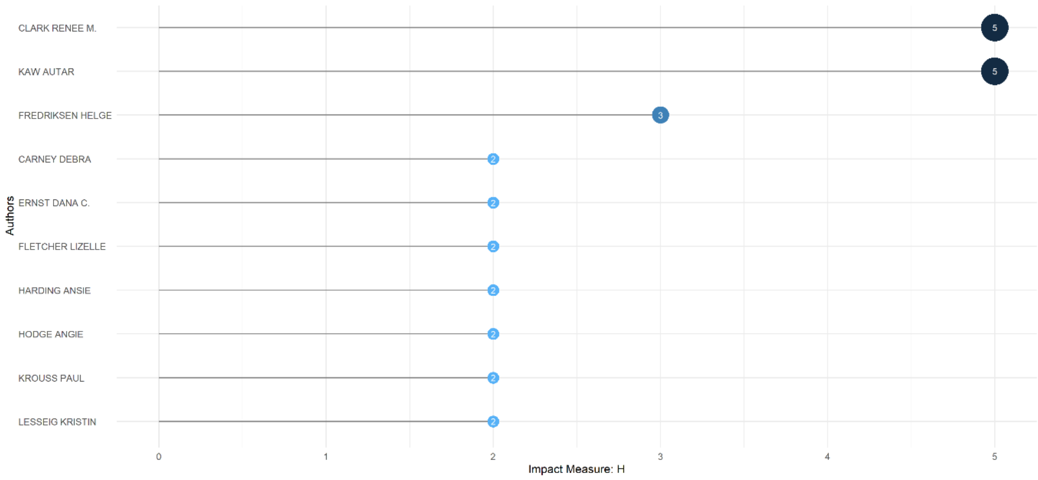

Figure 5. Author impact

Highly cited works align with major research themes, particularly in adaptive learning, digital tools, and student engagement, reflecting the centrality of these areas in shaping flipped classroom research. Clark Renee M. and Kaw Autar hold the highest local H-index of 5, indicating their extensive contributions, especially in adaptive learning and blended instructional models. Their prominent H-index demonstrates their central role in the development of flipped classroom discourse within university-level mathematics. Other notable contributors include Fredriksen Helge, Carney Debra, Ernst Dana C., Fletcher Lizelle, Harding Ansie, Hodge Angie, Krouss Paul, and Lesseig Kristin, each with an H-index of 2. While their impact is relatively modest compared to the top two authors, their work remains valuable in supporting research on the integration and application of flipped classroom methodologies in university mathematics. The distribution of H-index values points to a concentration of influential research among a small group of authors, suggesting that while the field draws from a broad base of contributors, a limited number of individuals play a leading role in advancing and shaping its development. Several factors may contribute to these low H-indices. These factors include authors being early-career researchers whose work has yet to gain visibility, the inherent constraints on publication volume due to the narrow focus of flipped classrooms in university mathematics, and the potential for the "local impact" analysis to be limited to a specific scope, excluding broader scholarly contributions. While the H-index is widely accepted, its limitations in contextualized analyses must be acknowledged. It does not capture contributions like teaching innovations or interdisciplinary work that fall outside the dataset’s scope. Low scores can also result from structural barriers, such as restricted access to high-impact publication venues. These findings reflect the challenges faced by researchers, particularly those at early stages of their careers, in gaining recognition within specialized educational research communities.

3.4.2. Most Relevant Authors

Figure 6 presents the most prolific authors in the field of flipped classrooms in university-level mathematics, based on the number of documents they have contributed. The x-axis represents the number of publications, while the y-axis lists the authors.

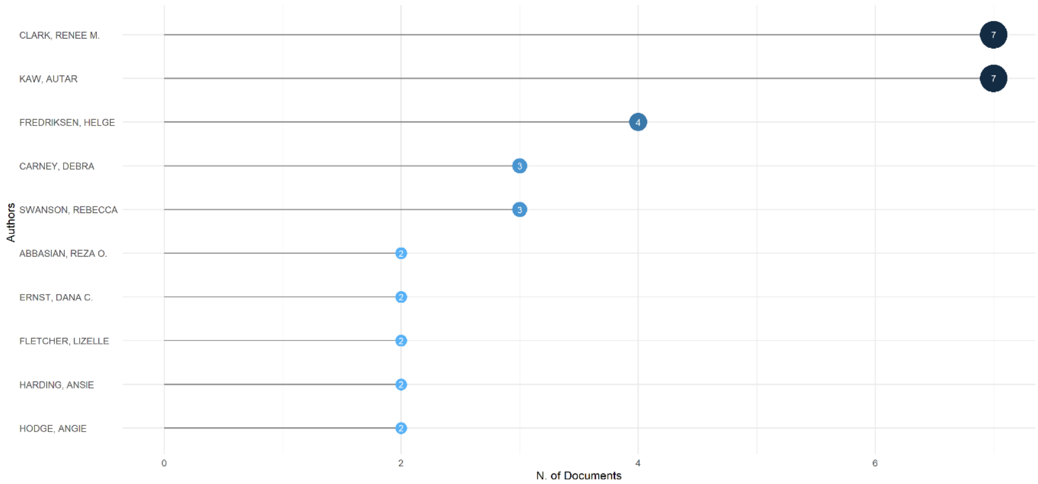

Figure 6. Most relevant authors

As previously noted in 3.4.1, Clark Renee M. and Kaw Autar emerge as leading contributors, with their collaborative work spanning adaptive learning strategies and pandemic-era adaptations, each with seven publications, indicating their pivotal role in advancing research on flipped learning methodologies and their applications in university-level mathematics. Their collaborative work focuses on three core areas: adaptive learning strategies (Clark et al., 2022; Clark & Kaw, 2020a), comparative instructional models (Clark et al., 2016), and the implications of online education during disruptive periods such as the COVID-19 pandemic (Clark et al., 2024). A significant portion of their research examines adaptive learning strategies in flipped classrooms, particularly within engineering and mathematics courses. Their studies emphasize the design and implementation of personalized learning pathways to enhance student engagement and comprehension, especially in technical disciplines requiring robust foundational skills (Clark et al., 2022). By tailoring instructional content to accommodate diverse preparedness levels, their work demonstrates how adaptive approaches can improve equity and outcomes in flipped environments.

A second strand of their research involves comparative analyses of pedagogical models, evaluating the efficacy of fully flipped, semi-flipped, and blended instructional frameworks in numerical method engineering course (Clark et al., 2016). These investigations provide critical insights into how varying degrees of flipped structure influence student performance and engagement, particularly in problem-solving and computational courses. Their findings inform best practices for balancing synchronous and asynchronous learning components to optimize educational delivery. Additionally, their collaborative efforts examine the impact of the COVID-19 pandemic on flipped classrooms (Clark et al., 2024), analysing the transition to emergency remote teaching. Their work demonstrates the adaptability of technology-enhanced learning during crises, showing how flipped methodologies supported instructional continuity and reduced disruptions. By assessing shifts in student perceptions and outcomes, their research informs strategies for optimizing flipped models across both in-person and remote contexts. Complementing individual contributions, the dissemination channels for flipped classroom research, particularly key journals, play a pivotal role in consolidating knowledge.

3.4.3. Most Relevant Sources

Beyond individual contributions, the dissemination of research is also shaped by the academic platforms that publish these studies. Figure 7 presents the most frequently used publication sources for research on flipped classrooms in university-level mathematics, offering a perspective on the journals that have played a central role in advancing knowledge in this field. The analysis of publication sources reveals distinct trends in the dissemination of flipped classroom research within university-level mathematics. *PRIMUS* (Problems, Resources, and Issues in Mathematics Undergraduate Studies) emerges as the foremost contributor, with 41 publications, solidifying its position as a primary platform for scholarship on innovative pedagogical strategies in university-level mathematics. Its dominance reflects the journal's central role in advancing discussions on flipped classrooms, active learning, and curriculum reform. Following *PRIMUS*, the *International Journal of Mathematical Education in Science and Technology* ranks second, contributing 13 publications. This indicates its emphasis on bridging pedagogical theory with technology-enhanced learning, particularly within mathematics education. Journals such as *Computer Applications in Engineering Education* and the *Journal of Statistics and Data Science Education* (8 publications each), along with the *Journal of Statistics Education* (7 publications), demonstrate cross-disciplinary interest in flipped classroom methodologies, especially in fields requiring computational rigor or data-driven instruction. These sources focus on applying flipped models to strengthen problem-solving and analytical skills in STEM disciplines.

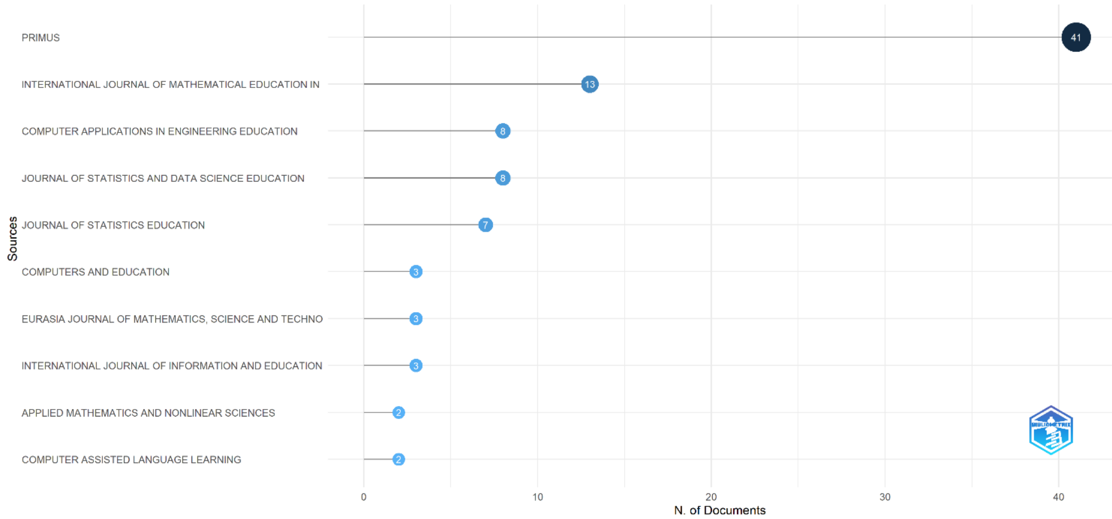

Figure 7. Most relevant sources

Mid-tier contributors, including *Computers and Education*, *Eurasia Journal of Mathematics, Science and Technology Education*, and the *International Journal of Information and Education Technology* (three publications each), reflect the broader integration of digital tools and educational technologies into mathematics instruction. Their contributions align with global shifts toward blended learning environments and the pedagogical use of information systems. Lower-output sources, such as *Applied Mathematics and Nonlinear Sciences* and *Computer Assisted Language Learning* (two publications each), suggest niche applications of flipped classrooms in specialized domains. For example, the inclusion of the latter points to exploratory intersections between technology-enhanced language learning and mathematics education, particularly in bilingual or interdisciplinary contexts. Collectively, these findings emphasize the interdisciplinary nature of flipped classroom research, spanning mathematics, statistics, engineering, and educational technology. The distribution of publications across journals illustrates both the centrality of pedagogical innovation in mathematics education and the growing emphasis on adaptive, technology-driven teaching practices in higher education.

3.5. Intellectual Structure of the Field

3.5.1. Most Global Cited Documents

Understanding the primary publication sources provides a foundation for exploring the impact of individual studies. Figure 8 presents the most globally cited publications in the domain of flipped classrooms within university-level mathematics, highlighting key works that have shaped the field and influenced subsequent research. Love et al. (2014) (289 citations), published in the *International Journal of Mathematical Education in Science and Technology*, is a cornerstone of flipped learning research. This study introduced early frameworks for integrating flipped methodologies in undergraduate mathematics, addressing both theoretical models and practical challenges. Similarly, Talbert (2014) (101 citations, *PRIMUS*) focused on discipline-specific adaptations, emphasizing curricular redesign to enhance student engagement in technical subjects. These foundational works remain central to contemporary discourse on flipped pedagogy. The role of digital tools in flipped classrooms has become a dominant theme. Sohrabi and Iraj (2016) (154 citations, *Computers in Human Behavior*) and Mohamed and Lamia (2018) (98 citations, *Computers & Education*) examine how technologies such as adaptive software and online platforms can optimize student outcomes. These studies connect theoretical pedagogy with practical implementation, demonstrating how flipped models can enhance problem-solving skills in STEM disciplines.

Recent works reflect evolving priorities Ahmad Uzir et al. (2020) (92 citations, *Journal of Computer Assisted Learning*) investigate artificial intelligence-driven adaptive learning systems, while Parra-González et al. (2020) (88 citations, *Sustainability*) link flipped pedagogies to sustainable educational practices. These studies indicate a shift toward personalized and environmentally conscious teaching models. Interdisciplinary applications are further exemplified by Wasserman et al.

(2017) (76 citations, *International Journal of Science and Mathematics Education*), which bridges mathematics and science education, and Haghighi et al. (2019) (75 citations, *Computer Assisted Language Learning*), which extends flipped methodologies to language instruction. This diversity demonstrates the adaptability of flipped classrooms beyond traditional STEM contexts. A summary of the five most globally cited documents is presented in Table 3 , which outlines their key contributions to flipped classroom research.

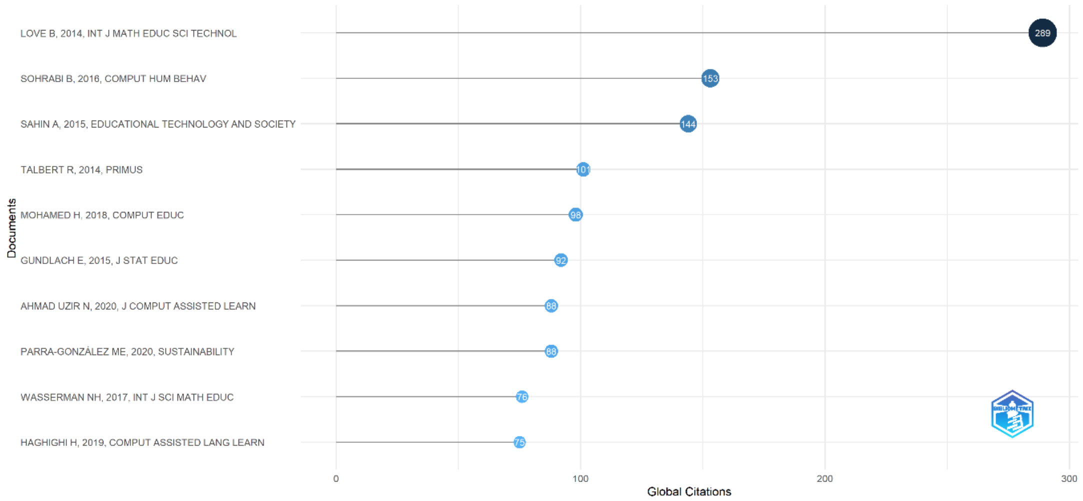

Figure 8. Most global cited document

Table 3. Summary of the five most globally cited documents

Paper	Total Citations	Summary
B. Love, A. Hodge, N. Grandgenett, and A. W. Swift, “Student learning and perceptions in a flipped linear algebra course,” *International Journal of Mathematical Education in Science and Technology*, vol. 45, no. 3, pp. 317–324	289	The study investigates the flipped classroom model in a sophomore-level linear algebra course, comparing it with traditional lectures. In the flipped model, students engaged with course materials like screencasts before class, while in-class time focused on interactive, problem-solving activities. Findings revealed that flipped classroom students showed greater improvement in exam performance over time, with similar final exam scores to the traditional group. Students in the flipped section expressed positive perceptions, appreciating the collaborative activities, instructional videos, and increased peer interaction. While the approach shows potential for enhancing learning and engagement in STEM education, the paper calls for further research to confirm its effectiveness in broader contexts.
B. Sohrabi and H. Iraj, “Implementing flipped classroom using digital media: A comparison of two demographically different groups perceptions,” *Computers in Human Behavior*, vol. 60, pp. 514–524, 2016	154	This research compares traditional lectures with flipped classrooms, emphasizing the benefits of interactive, learner-centred approaches. It reveals that flipped classrooms can enhance student engagement and collaborative problem-solving, as well as improve performance over time on sequential assessments. Students also appreciated the flexibility of instructional videos and peer interactions. These findings align with the broader pedagogical shift towards active learning in STEM disciplines, contributing valuable data to the growing discourse on flipped classrooms’ effectiveness in improving outcomes in mathematics education.
Sahin, A., Cavlazoglu, B., and Zeytuncu, Y.E., “Flipping a college calculus course: A case study,” *Journal of Educational Technology & Society*, vol. 18, no. 3, pp. 142-152, 2015	144	The study investigates the implementation of a flipped classroom model in a college calculus course, focusing on its impact on student preparation, performance, and perceptions. With a sample of 96 students, three out of ten course sections were taught using the flipped classroom approach, where students prepared through instructional videos before class. Results showed that students preferred video-based preparation over textbook reading and performed significantly better in quizzes during flipped sections. The flipped model also improved student confidence and engagement, with 83% reporting better preparation and 85% stating that videos enhanced their class performance. The study demonstrates the potential of the flipped classroom to increase academic achievement and student motivation, though limitations, such as its partial implementation and limited demographic representation, suggest the need for further research.
R. Talbert, “Inverting the Linear Algebra Classroom,” *PRIMUS*, vol. 24, no. 5, pp. 361–374	101	The paper explores the application of the inverted (flipped) classroom model in teaching linear algebra, focusing on its implementation and impact. The model shifts the initial content delivery outside the classroom via resources like videos, allowing class time to focus on

		complex problem-solving and interactive activities. Case studies include single-topic sessions, recurring workshops, and a fully inverted course. Results indicate improved student engagement, conceptual understanding, and success in higher-order tasks, with pre-class preparation and in-class collaboration being key components. Challenges include initial resistance from students, the time investment required for preparation, and the need for clear guidance. The study concludes that the inverted model holds significant promise for enhancing learning outcomes in mathematics education, particularly for courses like linear algebra that combine computational and conceptual learning.
H. Mohamed and M. Lamia, "Implementing flipped classroom that used an intelligent tutoring system into learning process," *Computers \& Education*, vol. 124, pp. 62–76	98	The paper explores the integration of flipped classrooms with an intelligent tutoring system (ITS) to enhance the learning process in a mathematical logic course at Annaba University, Algeria. It evaluates how the flipped model, supported by ITS, impacts students' performance, learning time, mental effort, and satisfaction. The flipped classroom approach shifted lecture content to pre-class videos, enabling interactive, problem-based activities during class. Results showed that the experimental group using the flipped classroom with ITS outperformed the control group in post-tests, required less learning time, and invested less mental effort while achieving higher learning gains. Key factors influencing students' satisfaction and continued intention to use flipped classrooms include perceived usefulness, self-efficacy, compatibility, and enhanced social interactions. The study concludes that flipped classrooms combined with ITS are effective in improving learning outcomes and student engagement, while recommending further research to generalize findings across diverse contexts and disciplines.

A key trend in the evolution of flipped classroom research is the growing role of artificial intelligence, adaptive learning, and sustainability-focused models. Early works focused on pedagogical frameworks and student engagement, but more recent studies incorporate intelligent tutoring systems, data-driven learning analytics, and personalized learning environments. For example, Mohamed & Lamia (2018) study on integrating intelligent tutoring systems represents a step toward automation in flipped learning, improving efficiency and student outcomes. Similarly, Parra-González et al. (2020) discuss the alignment between flipped classrooms and sustainable education, reflecting a broader shift toward resource-efficient teaching models. These advancements indicate that flipped learning is transitioning from a static pedagogical approach to a dynamic, data-driven educational model. While foundational and technology-focused studies dominate, gaps persist. Cultural adaptability, long-term efficacy, and discipline-specific barriers (for example, resource limitations in applied mathematics) have received limited attention. The rise of adaptive learning suggests opportunities for automation and personalized instruction, yet challenges in scalability and equity require attention. Additionally, integrating sustainability principles into flipped models could address cost-effectiveness in remote educational settings. This area presents significant potential for future innovation. The global citation impact of foundational works is reinforced by co-citation networks, which trace the intellectual lineage and interdisciplinary intersections within the field.

3.5.2. Co-citation Network

While citation counts indicate the impact of individual studies, a deeper understanding of research interconnections can be gained through co-citation analysis. Figure 9 delineates the intellectual structure of research on flipped classrooms in university-level mathematics, mapping how foundational works, empirical studies, and emerging trends intersect within the scholarly landscape. Bergmann (2012) occupy a central position in the network, reflecting their pivotal role in establishing flipped classroom pedagogy. Strong co-citation linkages to Freeman et al. (2014), Deslauriers et al. (2011), and Love et al. (2014) suggest that contemporary research remains strongly grounded in these early contributions. The enduring prominence of these works demonstrates the sustained influence of foundational theoretical frameworks, even as empirical studies continue to expand the evidence base. This dual emphasis indicates a field shaped by core principles while progressively integrating new approaches across diverse educational contexts. The red cluster, anchored by Lage et al. (2000) and Strayer (2012), centres on active learning theories and their alignment with flipped pedagogy. These studies draw on constructivist principles, with a focus on student engagement, instructional redesign, and cognitive benefits, reinforcing the compatibility between flipped models and learner-centred approaches. In contrast, the purple cluster, comprising Bishop and Verleger (2013), McGivney-Burelle and Xue (2013), and Abeysekera and Dawson (2015), addresses practical challenges such as faculty adoption barriers, student perceptions, and logistical complexities. The frequent co-citation of these works indicates their significance as benchmarks for evaluating the real-world implementation of flipped learning.

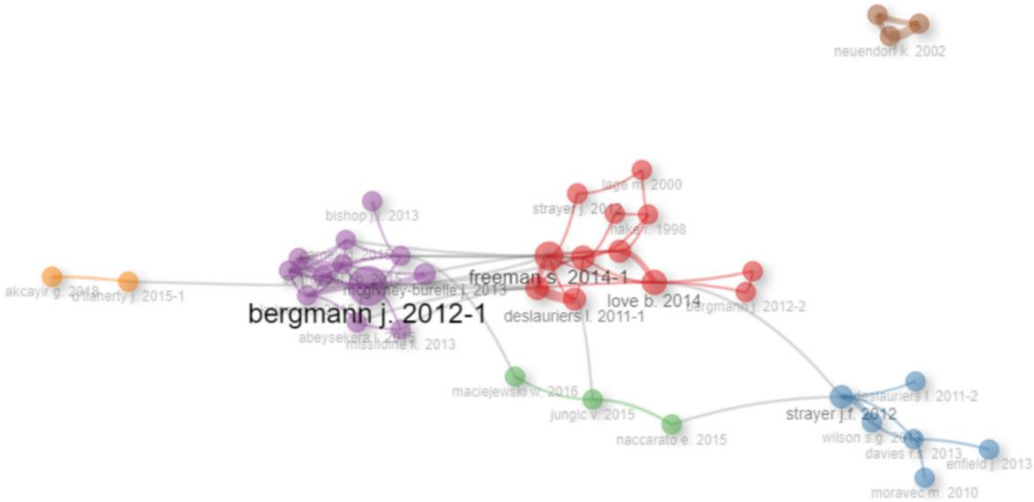

Figure 9. Co-citation network

Experimental studies dominate the blue cluster, featuring Deslauriers et al. (2011), Wilson Wilson (2013), and Davies et al. (2013). These works compare flipped and traditional classrooms, providing empirical evidence of enhanced student performance, engagement, and instructional effectiveness. Their strong co-citation ties reflect the field's emphasis on evidence-based validation. Meanwhile, the green cluster, represented by Jungić et al. (2015), Maciejewski (2016), and Naccarato and Karakok (2015), marks a shift toward discipline-specific applications. These studies explore flipped models in specialized mathematical subfields, such as calculus and applied mathematics, suggesting a growing focus on tailoring pedagogy to meet disciplinary needs. A notable outlier is the brown cluster, represented solely by Neuendorf (2002). Its isolation within the network points to a disconnect between methodological research on educational assessment and broader flipped classroom scholarship. The lack of co-citation linkages with other clusters reveals a critical gap: the absence of standardized metrics to evaluate flipped learning's long-term impacts. This methodological fragmentation stresses the need for integrative studies that combine content analysis, longitudinal assessment, and pedagogical design.

The co-citation patterns reveal a field still shaped by its theoretical origins yet increasingly diversifying into empirical and discipline-specific inquiries. However, the limited integration of emerging clusters, particularly those addressing methodological rigor and contextual adaptations, suggests opportunities for synthesizing foundational frameworks with innovative approaches. Future research should prioritize three pathways: first, interdisciplinary collaborations to integrate adaptive learning models and sustainability frameworks into flipped pedagogy; second, methodological advancements to establish consistent, scalable assessment criteria; and third, longitudinal analyses to examine how newer studies extend or challenge early theoretical assumptions. This analysis illuminates the dynamic evolution of flipped classroom research in university-level mathematics education, where foundational theories remain influential, but empirical validations and specialized applications are gaining traction. The field now faces the challenge of reconciling methodological gaps and fostering dialogue across research clusters. By addressing these issues, scholars can advance flipped classroom from a promising pedagogical strategy to a robust, evidence-driven paradigm. Future work must balance theoretical continuity with methodological innovation to ensure flipped models are both rigorously evaluated and sustainably adapted to diverse educational contexts. This co-citation analysis not only maps the field's theoretical roots but also reveals methodological gaps, setting the stage for discussing future research pathways in the concluding section.

Although the co-citation network identifies key publications shaping the field, it does not distinguish between different types of citation contexts. For instance, while (Bergmann, 2012) is frequently cited, it is unclear whether these citations primarily endorse their model or critique its limitations. Future research could integrate qualitative citation analysis to determine the nature of these references, providing deeper insight into how foundational works are utilized in flipped classroom used in university-level mathematics research.

4. DISCUSSION

The results of this bibliometric analysis provide a comprehensive overview of research on flipped classrooms in university-level mathematics, detailing publication trends, thematic patterns, author impact, and intellectual structure. While the findings demonstrate growing academic interest in flipped classroom methodologies, they also expose gaps in assessment standardization, international collaboration, and scalability. This discussion critically interprets the results by situating them within the broader educational research landscape and identifying key directions for future inquiry. The following subsections examine the evolution of research trends, thematic shifts in flipped classroom studies, global collaboration patterns, assessment challenges, scalability concerns, and disciplinary variations in effectiveness. Additionally, implications for future research are outlined to offer a roadmap for advancing flipped classroom pedagogy in university-level mathematics.

4.1. Research Trends and Evolution

The evolution of flipped classroom research in university-level mathematics over the past decade reveals distinct phases of growth, fluctuation, and stabilization. As shown in 3.1 there is an annual growth rate of 14.28%, reflecting sustained academic interest in this pedagogical approach. However, the fluctuations observed in specific years suggest that external factors, technological advancements, and shifts in educational priorities have influenced the research landscape. The early surge in 2015 marked an initial peak in flipped classroom studies, likely driven by the increasing adoption of active learning methodologies and technology-enhanced teaching strategies in higher education. During this period, universities and educators sought innovative instructional models to increase student engagement and improve learning outcomes, particularly in mathematics, where conceptual understanding and problem-solving skills are critical. However, this momentum was not sustained, as the sharp decline in 2016 suggests that research interest temporarily waned, possibly due to challenges in large-scale implementation, faculty resistance, and inconsistent student outcomes in early flipped learning experiments.

Between 2016 and 2018, research output remained inconsistent, reflecting a period of re-evaluation and refinement. During these years, scholars likely assessed the effectiveness of flipped classroom models, leading to improvements in instructional design, learning technologies, and integration with learning management systems (LMS) (Zainuddin & Perera, 2018). This phase also coincided with the growing adoption of blended learning environments, where institutions experimented with different instructional strategies to optimize student learning experiences (Cheng et al., 2019). From 2019 onward, a steady upward trend is evident, with publication numbers reaching their highest point in 2023. This surge aligns with the COVID-19 pandemic, which accelerated the adoption of remote, hybrid, and technology-assisted learning methodologies (Divjak et al., 2022). The necessity for flexible and resilient learning models during global disruptions likely drove the increased interest in flipped classrooms, as they provided structured yet adaptable instructional approaches that facilitated student-centred learning in digital and hybrid environments. Research during this period explored how video-based lectures, online assessments, and collaborative digital tools could enhance flipped learning experiences, making this approach even more relevant in university-level mathematics education.

However, the slight decline in 2024 raises critical questions about the future trajectory of flipped classroom research. This decline may indicate a saturation point in foundational studies, where core concepts have been well-explored, leading researchers to shift their focus toward more advanced educational models such as adaptive learning systems, AI-driven personalized instruction, and competency-based learning frameworks. Another possible interpretation is that the methodological challenges in flipped classroom research, particularly in standardizing assessment metrics (Roehling, 2018) and measuring long-term student learning gains (Baig & Yadegaridehkordi, 2023), may have led to a temporary slowdown in empirical studies. Despite these fluctuations, the sustained growth of flipped classroom research suggests that this pedagogical model continues to hold relevance in mathematics education. However, future research must go beyond merely demonstrating the benefits of flipped classrooms and focus on addressing long-term efficacy, discipline-specific adaptations, and integration with emerging educational technologies. Specifically, longitudinal studies are needed to assess whether flipped classrooms produce lasting improvements in mathematical proficiency and problem-solving skills over extended academic periods (Güler et al., 2023).

Additionally, comparative analyses between flipped, hybrid, and traditional instructional models could provide deeper insights into the contexts where flipped learning is most effective. Future research should also explore how institutional factors, faculty readiness, and student demographics influence the successful adoption of flipped classroom methodologies. These investigations will be crucial for guiding evidence-based policy recommendations and refining best practices in mathematics education. Overall, while flipped classrooms have established themselves as a key innovation in higher education pedagogy, their long-term sustainability, adaptability, and scalability remain open questions. The recent decline in publication numbers may signal a shift toward newer pedagogical paradigms, necessitating continuous research to ensure that flipped learning remains relevant in the evolving educational landscape.

4.2. Thematic Development and Emerging Research Areas

The thematic analysis of flipped classroom research in university-level mathematics shows a shift from foundational pedagogical frameworks toward the integration of advanced instructional technologies and adaptive learning strategies. Early studies focused on the feasibility and effectiveness of the approach, emphasising student engagement, active learning, and instructor roles. Recent investigations now incorporate digital tools, personalised learning systems, and interdisciplinary applications, reflecting broader trends in technology-enhanced education. The prominence of student engagement and learning systems in the keyword co-occurrence network (see Figure 3 underscores the sustained emphasis on learner-centred instruction. Increasingly, studies explore how interactive strategies, such as problem-based learning (Boye & Agyei, 2023) and collaborative exercises (Sujatha & Vinayakan, 2022), enhance knowledge retention and conceptual understanding in mathematics education. The link between flipped classroom methodologies and curriculum design suggests that researchers are examining how instructional models can address diverse learning needs (Zhao et al., 2021). Despite these advancements, a key gap remains in understanding long-term cognitive outcomes, particularly in complex problem-solving and higher-order thinking. Future research should go beyond immediate engagement metrics and assess whether flipped classrooms yield lasting improvements in mathematical proficiency.

The emergence of technology-enhanced instructional models suggests a growing interest in leveraging digital resources to optimize learning experiences (Abu Hassim & Shamsudin, 2023). Thematic clusters indicate a substantial increase in studies examining artificial intelligence and gamification as mechanisms for adaptive learning and performance tracking. These innovations enable real-time adjustments to content delivery based on individual student progress, potentially enhancing self-regulated learning (Khine, 2024; Strielkowski et al., 2024). Nevertheless, while the potential of these tools is evident, research remains fragmented regarding their effectiveness across different mathematical domains. Studies should focus on establishing clear implementation frameworks to assess their viability in educational settings, especially in the context of university-level mathematics. Although the field has witnessed considerable growth, certain areas remain relatively unexplored. Keywords such as data mining and digital storage appear at the periphery of thematic maps, suggesting limited inquiry into large-scale data analysis and learning analytics in flipped classrooms. The integration of big data methodologies could provide valuable insights into student learning behaviours, instructional effectiveness, and predictive performance modelling (Bai et al., 2021). Future investigations should explore how analytics-driven approaches can refine instructional strategies, allowing educators to make evidence-based decisions.

In contrast to the increasing focus on digital learning, studies addressing comparative effectiveness between flipped and traditional classroom models remain relatively scarce. Research has largely concentrated on individual case studies or small-scale interventions (Yan et al., 2018), limiting the generalizability of findings. Broader comparative analyses, particularly those conducted across different institutional contexts, are necessary to determine the conditions under which flipped methodologies yield the most significant benefits. Such studies could provide empirical validation for the effectiveness of flipped learning in specific mathematical disciplines, guiding educators in selecting appropriate instructional strategies. Overall, the thematic evolution of flipped classroom research reflects a dynamic shift toward technology-driven innovations and adaptive instructional design.

4.3. Challenges in Assessment and Standardization

Despite the increasing adoption of flipped classrooms in university-level mathematics, a persistent challenge in this field is the lack of standardized assessment frameworks for evaluating instructional effectiveness. Thematic mapping reveals that most studies rely on qualitative indicators, such as student perceptions, engagement levels, and instructor feedback, rather than quantifiable measures of long-term learning outcomes (Cevikbas & Kaiser, 2023; Cho et al., 2021; Jung et al., 2022). While these perception-based assessments provide valuable perspectives on student experiences, they do not fully capture whether flipped learning leads to sustained conceptual understanding and problem-solving proficiency. Without consistent evaluation metrics, it remains difficult to compare findings across studies, limiting the generalizability of flipped classroom research in university-level mathematics education (Tutal & Yazar, 2021). One of the primary reasons for this gap is the variability in flipped classroom implementations, which complicates direct comparisons (Yang et al., 2019). Studies differ in their course structures, instructional content, and integration of digital tools, leading to inconsistencies in reported outcomes. Furthermore, assessment criteria vary significantly, with some studies focusing on immediate performance improvements (Lai & Hwang, 2016; Yan et al., 2018), while others measure student satisfaction, retention rates, or participation levels (Clark & Kaw, 2020b; Kadry et al., 2014; Karjanto & Acelajado, 2022). This inconsistency calls the need for a standardized framework that accounts for both short-term learning gains and long-term skill retention.

As mentioned earlier, existing research also lacks rigorous longitudinal studies that track student learning beyond a single course (Fernández-Martín et al., 2020). While several studies report improved engagement and active participation (Cook, 2021), there is limited empirical evidence on whether these benefits translate into improved mathematical reasoning, analytical thinking, or academic performance in subsequent courses (Cheng et al., 2019). Developing a cohesive assessment model would help determine whether the flipped classroom approach fundamentally enhances learning efficiency or if its impact diminishes over time (Torres-Martín et al., 2022). Furthermore, since flipped classrooms emphasize active problem-solving and peer interactions, assessment strategies should extend beyond conventional exams and quizzes to include project-based evaluations, formative assessments, and competency-based performance metrics (Nouri, 2016).

Future research should investigate alternative assessment models that align more closely with the instructional goals of the flipped classroom. One promising approach is the use of cognitive learning analytics, which leverages AI-driven tools to track student progress, identify misconceptions, and tailor instructional interventions (Cukurova, 2024; Dai & Kang, 2025). By analysing student engagement patterns and performance trends, these tools can provide real-time feedback to support more personalized learning experiences. Another approach involves the development of mathematics-specific proficiency benchmarks that establish standardized rubrics for measuring conceptual mastery, procedural fluency, and higher-order thinking skills (Cook, 2021). Unlike traditional assessment methods, which often focus on procedural accuracy, these benchmarks enable a more comprehensive evaluation of students' understanding of mathematical principles, their ability to apply concepts, and their problem-solving agility. Such benchmarks would also promote consistency across flipped classroom studies, allowing researchers and educators to make meaningful comparisons between different instructional approaches. A third avenue for advancing assessment strategies is the implementation of competency-based assessment models, which evaluate students based on their ability to apply mathematical concepts in real-world or interdisciplinary contexts (Xu et al., 2023). Rather than relying solely on traditional exams, this approach emphasizes students' capacity to transfer knowledge and solve complex problems beyond routine exercises. Competency-based assessment aligns well with the active and applied learning principles central to flipped classrooms, making it a suitable alternative for measuring student progress in university-level mathematics (Wu et al., 2024).

The absence of such structured evaluation mechanisms not only hinders research comparability but also makes it difficult for educators to refine and optimize their flipped classroom strategies. Future research should prioritize the development of a universal assessment framework, ensuring that flipped learning outcomes can be measured consistently across diverse academic settings. This would enhance the credibility of flipped classroom research and provide data-driven insights for improving instructional practices in university mathematics education.

4.4. Sustainability and Scalability of Flipped Classroom Models

While the flipped classroom approach has been widely adopted in university-level mathematics education, its long-term sustainability and scalability remain notable concerns. The success of this instructional model depends not only on its effectiveness in enhancing learning outcomes but also on its feasibility for widespread implementation across different institutional and technological contexts. Thematic mapping reveals that research has primarily focused on individual case studies or small-scale interventions, with limited attention to the broader challenges of adapting flipped learning to diverse educational environments, faculty workload, and resource availability. One of the primary barriers to scalability is the infrastructure and resource intensity required for effective flipped classroom implementation (Al-Samarraie et al., 2020). Many flipped models rely on high-quality video lectures, interactive digital platforms, and online assessments, which require substantial technological investment (Loizou, 2022). While well-funded institutions can integrate these resources seamlessly, universities with limited digital infrastructure, financial constraints, or unequal student access to technology may struggle to adopt the model effectively (Ng, 2015). The unequal distribution of technological resources raises concerns about educational equity, as students from underprivileged backgrounds may face difficulties engaging with digital learning materials outside the classroom (Nouri, 2016).

In addition to technological concerns, faculty workload and instructional preparation present significant challenges to sustainability (Rotellar & Cain, 2016). The transition from traditional lecture-based instruction to flipped classroom requires educators to redesign curricula, create pre-class materials, and develop interactive learning activities. Unlike traditional teaching, where instructors primarily focus on in-class lectures, flipped classrooms demand continuous content creation, digital resource management, and active facilitation of in-class problem-solving sessions. Without institutional support mechanisms, such as professional development programs, workload adjustments, and incentives for faculty engagement, the widespread adoption of flipped classroom may be difficult to sustain. Despite these challenges, recent research suggests that flipped classroom has the potential to enhance cost-effectiveness and instructional efficiency in the long run (Cheng et al., 2019). Once developed, video lectures and digital content can be reused across multiple courses, reducing the need for repetitive in-class instruction. Moreover, adaptive learning technologies can automate certain aspects of instruction, allowing personalized student learning pathways and reducing the time faculty spend on remedial teaching (Hu, 2025). However, studies have yet to determine the long-term cost-benefit ratio of flipped learning models, particularly in large-scale implementations where the initial investment in content creation may be substantial.

To ensure sustainable and scalable adoption, future research should explore how flipped methodologies can be implemented with minimal reliance on digital tools, making them accessible to institutions with limited technological resources. Faculty training and workload management strategies should also be examined to identify ways to support instructors through pedagogical training programs, institutional incentives, and collaborative content-sharing platforms (Mengesha et al., 2024). Additionally, developing scalability frameworks that adapt flipped learning principles to large-classroom environments, interdisciplinary curricula, and varying levels of student preparedness will be essential (Piccoli et al., 2020). Addressing these factors will be crucial in ensuring that the flipped classroom approach is not only educationally effective but also feasible for widespread, long-term implementation. By refining instructional models, reducing technological barriers, and supporting faculty, the flipped classroom can become a sustainable and adaptable pedagogical approach, capable of transforming mathematics education especially in university across diverse academic settings. Addressing these factors will be crucial in ensuring that the flipped classroom approach is not only educationally effective but also feasible for widespread, long-term implementation.

4.5. Disciplinary Variations in Flipped Classroom Effectiveness

In addition to issues of scalability and sustainability, a significant gap in the literature pertains to comparative analyses across mathematical subfields. Most flipped learning research in university mathematics has focused on widely taught subjects such as calculus (Fung et al., 2024; Kadry et al., 2014), linear algebra (Talbert, 2014), and statistics (Wilson, 2013), likely due to their prevalence in undergraduate curricula and the ease of integrating computational problem-solving exercises into flipped models. However, the effectiveness of flipped learning in pure mathematics, applied mathematics, and specialized areas such as mathematical modelling and discrete mathematics remains underexplored. Different branches of mathematics require distinct cognitive skills, and it is essential to determine whether flipped methodologies are equally effective across disciplines with varying levels of conceptual abstraction. Understanding how instructional strategies align with disciplinary demands would provide valuable insights into optimizing flipped learning approaches for diverse mathematical courses.

For instance, courses in pure mathematics, such as real analysis and abstract algebra, often emphasize theorem-proving, logical reasoning, and deep conceptual understanding. These courses typically require students to construct rigorous mathematical arguments, develop formal proofs, and engage with high levels of abstraction. Given the complexity of these tasks, flipped learning in proof-based courses may require additional scaffolding and structured guidance to ensure that students can effectively transition from pre-class exposure to in-class problem-solving (Talbert, 2015). Unlike computational courses where students can reinforce learning through repeated practice, proof-based subjects may benefit more from guided problem-solving sessions, instructor-led discussions on proof strategies, and collaborative theorem construction exercises (Roehling, 2018). Without such instructional adaptations, students may struggle with the cognitive load imposed by highly abstract pre-class materials (Wirth et al., 2024).

In contrast, applied mathematics courses, which integrate mathematical concepts with real-world applications, may be more naturally suited to the problem-solving and collaborative aspects of flipped learning. Fields such as numerical methods, operations research, and mathematical modelling often involve computational techniques that can be introduced effectively through pre-class videos, interactive simulations, and coding exercises, allowing students to focus on application-based learning during in-class sessions (Yohannes & Chen, 2024). The flipped classroom model may also facilitate interdisciplinary learning in applied mathematics, enabling students to explore cross-disciplinary applications in engineering, economics, and data science. However, the extent to which flipped models enhance conceptual understanding in applied mathematics remains uncertain, as students may focus on procedural fluency rather than the underlying mathematical principles (Güler et al., 2023). Future research should investigate whether flipped instruction fosters deeper conceptual engagement in applied mathematics compared to traditional lecture-based approaches.

Furthermore, research should explore the differential effectiveness of flipped learning in lower-division versus upper-division mathematics courses. Lower-division courses, such as introductory calculus, are often taught in large lecture settings and include students with varying levels of mathematical preparedness (Cronhjort et al., 2018). In this context, flipped learning may serve as a remedial tool, providing students with opportunities to engage with fundamental concepts before class and reinforce their understanding through structured in-class exercises. Studies suggest that flipped learning is particularly effective in courses with high dropout rates, as it allows students to revisit materials at their own pace and seek additional support during active learning sessions (Kattel et al., 2024). However, given that lower-division courses often include students with diverse academic backgrounds and levels of self-regulation, the effectiveness of flipped learning may depend on students' ability to engage with pre-class content independently. Future studies should assess whether structured interventions, such as instructor-led review sessions or embedded formative assessments, improve student engagement and learning outcomes in lower-division mathematics.

Upper-division courses, by contrast, tend to have smaller enrolments and involve higher levels of mathematical abstraction. These courses often require students to engage in complex problem-solving, abstract reasoning, and independent inquiry, making flipped learning potentially beneficial for fostering deep engagement and active participation (Kensington-Miller et al., 2016). However, the effectiveness of flipped instruction in upper-division courses may depend on how well students can navigate pre-class materials without direct instructor guidance (Feudel & Fehlinger, 2023). While students in advanced mathematics courses are generally more accustomed to self-directed learning, challenges may arise if pre-class content does not adequately prepare them for in-depth in-class discussions (Allison, 2021). Investigating how flipped methodologies can be adapted for upper-division courses through strategies such as pre-class guided notes, structured problem sets, and peer collaboration frameworks would offer valuable insights for optimizing flipped learning in support of advanced mathematical reasoning.

Additionally, comparative studies should assess whether flipped instruction is more effective in computation-based versus proof-based mathematics courses. Courses that emphasize algorithmic thinking, such as differential equations and numerical analysis, may benefit from flipped learning due to their reliance on step-by-step procedural learning, which can be reinforced through interactive pre-class tutorials and coding exercises (Johnston, 2017). In contrast, proof-heavy courses, such as topology and real analysis, may require more structured in-class discussions and instructor guidance to support students in developing logical reasoning and formal proof-writing skills (Feudel & Fehlinger, 2023). Investigating the interplay between flipped instruction and different cognitive demands in mathematics would provide a clearer understanding of how to design discipline-specific flipped learning models.

Future research should examine how the outcomes of flipped learning differ across various branches of mathematics. While applied and computational courses often support problem-solving and interactive activities, courses that emphasize proofs may require additional support to help students move effectively from pre-class preparation to in-class work. Determining the most suitable instructional strategies for these distinct course types would inform the development of tailored flipped learning models. Another important direction is to evaluate the effectiveness of flipped learning in lower- and upper-division mathematics courses. In large, lower-level classes with students from diverse backgrounds, flipped learning can reinforce core concepts through structured pre-class activities and guided practice during class. However, its effectiveness may depend on students' readiness to engage independently with learning materials before class. Further research should consider whether structured supports, such as instructor-led review sessions or regular formative assessments, can enhance student engagement and achievement in these contexts.

Upper-division courses, with their smaller enrolments and higher levels of mathematical abstraction, demand complex problem-solving and independent inquiry. Flipped learning has the potential to foster deeper engagement, but its effectiveness may depend on whether students can navigate pre-class materials without direct instructor guidance. Investigating strategies such as pre-class guided notes, structured problem sets, and peer collaboration could help optimize flipped learning for advanced mathematical reasoning. By systematically investigating these questions, researchers can refine flipped learning methodologies to enhance student engagement, conceptual understanding, and instructional effectiveness across diverse mathematical disciplines. Expanding flipped learning research beyond widely studied courses such as calculus and statistics to include pure and applied mathematics, as well as interdisciplinary fields, would contribute to a more comprehensive understanding of how this instructional model can be optimized for different learning contexts.

5. CONCLUSION

This bibliometric study examined a decade (2014–2024) of flipped classroom research in university mathematics, analyzing publication trends, key contributors, thematic developments, and the intellectual structure of the field. Findings show steady growth in output post-2020, driven by the shift toward blended and technology-supported teaching. Dominant themes include student engagement, digital tools, curriculum design, and the integration of artificial intelligence and adaptive learning. Citation patterns confirm the influence of a small group of foundational studies. However, key research gaps persist: most studies provide only short-term outcomes, lacking data on long-term learning gains and mathematical reasoning development. Inconsistent assessment practices hinder cross-study comparison. Furthermore, research is concentrated on introductory courses (e.g., calculus), leaving advanced and proof-based subjects understudied. Practical barriers, including faculty workload and scalability across institutions, remain significant. Future work should adopt longitudinal designs, establish clearer evaluation standards, and compare flipped instruction across diverse branches of mathematics. Integrating adaptive technologies and learning analytics offers substantial potential to enhance instructional effectiveness. Addressing these issues is essential to strengthen the evidence base and optimize the use of flipped classroom approaches in university mathematics.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest

AUTHOR CONTRIBUTION
Amirul Aizad Ahmad Fuad: Conceptualization, Methodology, Supervision, Writing - Original Draft, Writing - Reviewing and Editing. Ashraff Ruslan: Data Curation, Software, Validation, Writing - Reviewing and Editing. Anam: Visualization, Formal Analysis, Investigation. Mujahid Abdullahi: Conceptualization, Methodology, Investigation. Yunusa Aliyu Hadejia: Conceptualization, Formal Analysis, Investigation.

DATA AVAILABILITY
All data generated or analysed during this study are included in this published article.

DECLARATION OF GENERATIVE AI
During the preparation of this work, the authors used ChatGPT (OpenAI) to assist in language refinement and structural organization of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Not applicable.

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