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# The Challenges of STEAM Education ¿What is Expected of a Bibliometric Approach to the Training of Mathematics Teachers?

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## ABSTRACT

Over the past decades, the STEAM (Science, Technology, Engineering, Arts and Mathematics) educational approach was conceived as a strategy aiming at integrating previously isolated disciplines to develop critical thinking and creativity through complex problem-solving processes from an interdisciplinary perspective. Its implementation at different educational systems revealed certain challenges primarily related to teacher training and specifically mathematics teacher training. This article proposes to answer the question, within the challenges of STEAM education: What is expected of a bibliometric approach in mathematics teacher training? °This is achieved through a bibliometric analysis of 444 articles from Q1 and Q2 quartile journals, encompassing 1,768 conceptual terms defined by 1,474 authors. The results of the thematic evolution analysis identify fifteen clusters of co-occurring conceptual terms, as well as current and emerging trends in research on mathematics teacher competencies for STEM education. These findings empirically substantiate the identification of priority lines of research that must be accompanied by qualitative studies aimed at formalizing the dynamics of correlation between the identified terms, conceptual constructs lying beneath them, and their evolution from rudiments.

**Keywords:** Bibliometric, Thematic Map, Education STEAM, teacher professional, bibliometrix, Python

## INTRODUCTION

In the last five years, STEAM (Science, Technology, Engineering, Arts and Mathematics) has been positioned as a pedagogical strategy to address educational challenges towards digital transformation, social complexity and 21st century skills. The recent literature strongly agrees on results about how interdisciplinary integration within the STEAM model creates composite links of creative thinking development processes with problem-solving and meaningful learning but also highlights structural ,pedagogical and training chal lenges in effectively implementing the same wherein lies an important concern regarding the role o f mathematics teachers [1], [2], [3].

The major challenge, as noted by recent research, lies in the professional development of teachers and more particularly in their capacity to competently integrate mathematical content with other STEAM disciplines at contextual and pedagogical levels. A few studies revealed that while there is general acceptance of the STEAM approach among most teachers, specific training aimed at integrating new technologies-in-use methodologies actively and creatively inside classrooms is lacking among many of them [4], [5], [6]. Thus apparently scant even tentative impact these educational proposals have found so far. Within such a scenario it is exactly math teachers who play leading roles because of both cross-curricular functions they perform within the STEAM curriculum.

Recent literature exploits both opportunities of the most new advanced digital resources such as virtual reality, interactive simulations and sharing or collaborative platforms available to support STEAM teaching, [7], [8] in raising even more demands on teachers' pedagogical techno logical and creative skills. The changes involve not only conceptual competences but competence in the design of interdisciplinary learning experiences , authentic assessment and adaptation to different educational contexts where significant gaps still exist aspects ofinitaland ongoing trainingfor mathematics teachers [9], [10].

In this context, bibliometric analysis remains among the main methodological instruments for a systematic comprehension of the evolution of research on STEAM education and mathematical teachers' training. Trends facilitate the identification of thematic trends as well as patterns in academic collaboration and prevailing methodological approaches and gaps in research that provides empirical evidence for future investigations intended at teacher-training policies Moreover through this approach it is quite apparent how certain concepts have taken central places within recent scientific literature- concepts such as creative thinking; professional teaching competence; technological integration or interdisciplinary learning.

A bibliometric analysis of mathematics teacher education literature helps determine if the existing works have adequately discussed STEAM education methods pedagogical, content-specific and technological dimensions, and which professional competencies have attracted specific research attention while some remain unexplored [4], [13]. Hence bibliometrics provides not only descriptive information but also analytical and forward-looking information. It assists in developing a more robust conceptual basis for framing teacher education curricula to address the present challenges of STEAM education.

In summary, the current challenges of STEAM education are not limited to the curricular integration of disciplines, but extend to the need to strengthen the professional competencies of mathematics teachers through training approaches based on scientific evidence. In this context, bibliometric analysis of recent research is presented as a relevant and necessary strategy for understanding the evolution of the field, guiding academic decision-making, and contributing to the development of innovative, creative, and contextualized teaching practices within the framework of STEAM education [12].

In this sense, the bibliometric approaches applied to exploring the challenges of STEAM education in the development of mathematics teachers' professional competencies are limited, and the proposals made are only focused on establishing frameworks for the methodology applied in STEM education [14]. Therefore, this article seeks to answer the following question regarding the challenges of STEM education: What is expected of a bibliometric approach to the training of mathematics teachers?, and the corresponding hypothesis:

H1: Bibliometric analysis will allow us to determine the challenges in developing the competencies required by mathematics teachers in the context of STEM education.

This hypothesis is based on the growing attention that teacher training has received within the field of STEM education, particularly regarding the competencies needed to face the challenges of a dynamic, technological, and interdisciplinary problem-solving educational environment. These trends emphasize mastery of disciplinary content and the development of pedagogical, technological, and innovation skills. For example, several reviewed studies highlight that the educational transformation promoted by STEM demands new digital, didactic, and collaborative competencies from teachers, especially at the secondary and initial teacher training levels.

In this sense, a bibliometric approach is highly relevant, making it possible to map the thematic evolution in the scientific literature, identify the most frequently addressed challenges in mathematics teacher competencies, the training methodologies used, and explore the trends in the analyzed bibliometric measures. Bibliometrics also helps in the identification of thematic gaps and emerging trends. It provides information on relevant co-authorship networks that deepen the understanding of the state of the art in mathematics teacher training.

This document is organized into section 2, Implications from Literature. Section 2, Methodology contains the methodology applied for bibliometric analysis. Section 3, Results contains an exploration of main measures and results of bibliometric analysis. Section 4, Discussion contains an analysis of results obtained and validation of hypothesis. Section 5, Conclusions contains the contributions made by this article and its implication as future work.

## IMPLICATIONS OF THE LITERATURE

### Competencies of Mathematics Teachers in STEAM Education

Recent scientific literature on STEAM education shows a growing consensus regarding There is a strategic role of mathematics teachers in STEAM education to implement the approach successfully through effective interdisciplinarity. Mathematics forms both a structural axis of the STEAM model and as transversal language articulating science, technology, engineering, and arts. Therefore this central role demands specific professional competencies from mathematicians which meanwhile are absent or have hardly been developed forming one of the main challenges reported in literature [15], [16].

The results show that, from the point of view of pedagogy, one of the most relevant competences for mathematics teachers in STEAM contexts is having abilities to design interdisciplinary learning experiences by integrating mathematical content with real-world problems and technological contexts as well as activities related to creativity. Many teachers still apply traditional approaches based on transmitting content [6], [17], [18]. Such an approach prevents connecting mathematics with other STEAM disciplines and allows very limited room for developing creative thinking as well as resolving complex problems within students. This shortfall lies in enhancing teaching competences oriented toward project-based learning involving authentic problems and curricular integration.

The literature emphasizes as a challenge for mathematics teachers the meaningful integration of digital tools and new technologies within STEAM classrooms. Among technological competencies, there is an increasing offer of digital resources-such as simulations, virtual environments, interactive platforms, and educational applications-which can be properly used only by highly competent teachers in using technology itself and in articulating clear mathematical learning objectives through such tools [19], [20]. A recurring limitation emphasized by most studies reviewed to report on the quality with which STEAM is implemented is lack or insufficient specific training provided to pre-service/in-service teachers.

Another key competence the literature describes is this capacity for the encouragement of creative thinking and development of higher-order mathematical reasoning within interdisciplinary contexts. The analyzed articles stress that "thinking creativity" should not be considered as something outside mathematics but as an internal aspect of mathematical thinking when exploration, modeling, conjecture formulation, and solution to open-ended problems are encouraged [21], [22]. However, it also reveals that many teachers find difficulty in integrating creative strategies into mathematics instruction due to either inadequacies in their pedagogical training or curricular pressures focused on standardized results [23].

Recent studies share the results of an urgent need to improve formative and authentic assessment skills among mathematics teachers parallel to the main principles of STEM education. Literature provides evidence that abilities related to creativity or the application of knowledge to mathematical content through interdisciplinary connections cannot be captured by standardized tests measuring only algorithmic procedures designed as surrogates for broader habilities [18], [24]. Teachers should therefore focus on developing their ability in assessment criteria design, portfolio, and project-based assessments which document holistic learning outcomes within a STEM context.

A bibliometric analysis of scientific publications based on the retrieval equations defined in the methodology indicates that these teaching abilities represent recurring and closely related thematic areas in the current literature. Co-occurrence patterns and themes evolution suggest "framing" is gradually shifting-from being heavily content oriented to emphasize teacher professional development, technology integration, and creative thinking approaches as a new mode of mathematics education [15], [25], [26]. Again this moves training proposals further upstream as guided by gaps emerging out of harnessing evidence through a bibliometric approach that synthesizes training programs for teachers aligned with current demands emanating from STEAM education.

The literature implies that a training strategy aimed at developing, enhancing, and sustaining competencies of mathematics teachers in STEAM education should be systematic, evidenced-based-in-practice-oriented. Training programs integrate articulated pedagogical components-technological-and-creative initial and continuous development overcoming the limitations of fragmented approaches to the potential of the STEAM model [16]. A bibliometric perspective can not only provide in-depth insights into scientific trends, but also offer important recommendations for designing educational policies in the field of teacher training based on established scientific trends.

**The Interquartile Level in Scientific Publications**

An important aspect in understanding how professional competence is integrated by mathematics teachers within the STEM subjects, can be observed through recent scientific publications of a slightly lower level (Q2-Q3) that move beyond theoretical approaches, more preferred in first-quartile(Q1) journals. These articles ensure better balancing between methodological rigor and pedagogical applicability and transferrable aspects for developing teacher training to apply eventually in real classroom settings.

Works analyze the integration between educational technologies and digital competencies with interdisciplinary approaches as central elements for mathematics teachers' performance in STEM environments. There is a strong presence of such works or, in other words, this is one of the most frequently found topics within the collected articles. Recent bibliometric studies reveal that much of the work published in Q2-Q3 discusses the adoption of augmented reality, virtual reality, and emerging technologies, emphasizing their influence on students' motivation, attitude, and interest. All these aspects are directly related to the teacher's ability to develop contextualized and meaningful mathematical experiences [27], [28].

 

Interquartile studies show increasing attention towards pedagogical and didactic competence, mostly in the application of active methodologies, computational thinking, and evidence-based practice. An evolutionary analysis of educational technology shows that though its most advanced developments appear in Q1 journals, the practical classroom applications for mathematics teachers more frequently appear in Q2–Q3 journals where implementation strategies and curriculum adaptation are discussed [29], [30].

At the interquartile level from the institutional perspective, research on higher education and sustainable development also underlines the needs of competencies in teachers to articulate STEM content with social, ethical, and contextual issues [31]. Besides this, research works on artificial intelligence applied to education-in-teacher-training programs emphasized-from Q2-Q3-more significantly than pedagogically feasible critical aspects for mathematics teachers who are in educational innovation processes even though they are dominated by Q1 publications [32].

Overall, the literature of the last five years contains this level constitutes a bridge between high-impact research and educational practice gives valuable evidence toward developing professional teaching competencies in STEM education, particularly mathematics, where articulation between disciplinary content, pedagogy and technology is crucial for the quality of learning.

**Application of the PRISMA Methodology**

The use of the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) has been established in the literature over the past five years as a methodological benchmark for supporting transparency, rigor, and reproducibility in review studies related to STEM education and specifically to the analysis of professional competencies of mathematics teachers. PRISMA provides a basis upon which processes can be systematically structured in identifying, screening, eligibility, and inclusion of studies thereby reducing bias and strengthening validity of findings.

More recently, PRISMA has been used to support the organization of large volumes of scientific literature by separating relevant articles according to their design, quality, and level of evidence. This is particularly useful for research analyzing pedagogical strategies and teaching competencies because such studies are often interested in empirically supported educational practices that can be transferred to a mathematics classroom within an STEM context [16]. It also allows study classification based on publication quartile- hence providing clarity regarding analyzed evidence's quality as well as impact. Other socio-emotional competence oriented holistic teacher education oriented studies reveal that using PRISMA helps bring together scattered results into consistent relationships between teachers' professional competencies with student learning outcomes [33]. Such systematization strengthens recent scientific based pedagogical decision making among mathematics teachers.

In the area of educational innovation and use of technologies, PRISMA has also been implemented to review research works on digital resources and technological environments in education to identify methodological trends and approaches with greater potential for teacher training [34], [35]. The strict application of PRISMA provides that hence STEM literature is analyzed based on clear and replicable criteria, therefore standing an understanding and development of teaching competencies in mathematics from a sound methodological perspective.

**Application of Bibliometrics in this Field of Study**

Over the past five years, bibliometrics has been consolidated as a strategic methodological tool capable of providing an objective analysis regarding the evolution, structure and trends of research in STEM education related to mathematics teacher professional competencies. Through an analysis focussed on scientific productivity and impact indicators at journal level together with co-authorships, keywords or collaboration networks; this study aims at identifying both established/dominant thematic areas as well as emerging ones which orientate either teacher training or their performance evaluation.

Recent bibliometric analyses show a steady increase in scientific production on the integration of technology, computational thinking, and pedagogical innovation in education areas directly associated with the competencies currently demanded of mathematics teachers in STEM contexts [36], [37]. The analyses permit an understanding not only of the number of publications but also their quality by source, since they emphasize a concentration of research work in Q1 and Q2 journals. That is a sign of academic maturity. It also increases recognition and influence among the scientific community.

At an institutional level, a bibliometric analysis of the evolution of research on higher education notes that only very recently have teacher education, curriculum development, and interdisciplinary research become core issues of higher education [13]. Hence, this study occupies an important niche in providing rationales for mathematics teacher education programs to harmonize them with up-to-date scientific trends demanded by practical STEM environments.

Bibliometric analysis helps in understanding the impacts that new technologies, like artificial intelligence and digital learning environments, have on education while unveiling gaps in research and prospective areas for enhancement in teacher education [38], [39]. Therefore, this kind of analysis is highly significant for mathematics teachers since it reveals both technological and methodological capacities related to educational innovation.

The use of bibliometrics in this field provides backup to the systematic analysis of literature and helps to ground, through scientific evidence, the development of professional competencies for mathematics teachers in STEM education. This later allows academic and pedagogical decision-makers to base their actions on real trendsconsidered here as proven and justified by scientific knowledge instead of supposed ones.

### Centrality Cluster Visualization (Thematic Map)

Cluster visualization using Thematic Maps remains one of the leading analytical tools in recent bibliometric studies because it permits an organized display of conceptual development within a discipline, based on centrality and density metrics. In this light, themes are detected by communities found with the Walktrap algorithm in keyword co-occurrence networks under an assumption that closely related nodes have similar paths through the network. It is quite effective at discovering coherent clusters both established and emergent lines reflected by research in STEM education [40], [41].

Callon's centrality helps in determining the interaction of each cluster with the rest of the network to distinguish between driving themes, core themes, emerging and declining themes. In STEM education, conceptual cores have frequently been identified which are linked to the development of professional teaching competencies such as computational thinking, technological integration or active methodologies in mathematics teaching [42]. High-centrality clusters reflect transveral competencies broadly connected to other areas of knowledge that emphasize their strategic relevance in teacher training.

Furthermore, through the Thematic Map visualization with Walktrap and Callon's centrality, it is possible to interpret the way certain teaching competencies move from a peripheral approach to a central position inside the field. According to recent bibliometric studies, competencies regarding the use of digital technologies-artificial intelligence-educational data analysis are becoming more centered on core issues regarding mathematics teachers in STEM contexts [43], [44]. This fact has an implied key importance for guiding teacher training programs based on scientific evidence.

To sum up, the application of the Walktrap algorithm and Callon centralization in visualizing theme clusters supports the structural analysis of literature. It provides a clear perspective on how different competencies of mathematics teachers for STEM education are set, ranked, or prioritized by recent scientific trends making such pedagogical or curricular decision choices easy to actualize.

## METHODOLOGY

### Document Selection

The PRISMA methodology for reviews [45], was applied to the document selection process. As a first step, the two databases that provide the most bibliometric measures, Scopus and Web of Science [46], were selected. These databases also have a high level of reliability and prestige for the research they index. The respective search equations were developed and executed on their respective platforms (see Table 1), yielding a total of 710 articles retrieved in Bib format.

**Table 1.** **Search equation**

| **Scopus** | **Total** |
|---|---|
| TITLE-ABS-KEY ( ( "STEM education" OR "STEM" ) AND ( teacher* OR educator* OR "science teacher*" OR "math* teacher*" ) AND ( "secondary education" OR "middle school" OR "high school" OR "secondary school" OR "educacion media" OR "escuela secundaria" ) AND ( "professional development" OR "professional challenges" OR competencies OR "teaching skills" OR "career development" OR "teacher readiness" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) | 310 |
| **Web Of Science** | |
| ( "STEM education" OR "STEM" ) (All Fields) and ( teacher* OR educator* OR "science teacher*" OR "math* teacher*" ) (All Fields) and ( "secondary education" OR "middle school" OR "high school" OR "secondary school" OR "educacion media" OR "escuela secundaria" ) (All Fields) and ( "professional development" OR "professional challenges" OR competencies OR "teaching skills" OR "career development" OR "teacher readiness" ) (All Fields) Document Types: Article | 400 |
| **Summary** | **710** |

 

For the selection and exclusion of documents, the criterion of the upper quartiles Q1 and Q2 was considered, associated with each of the journals in which the documents were published. This criterion will allow the exploration of scientific production supported by the prestige of the journals of origin, see the figure below.

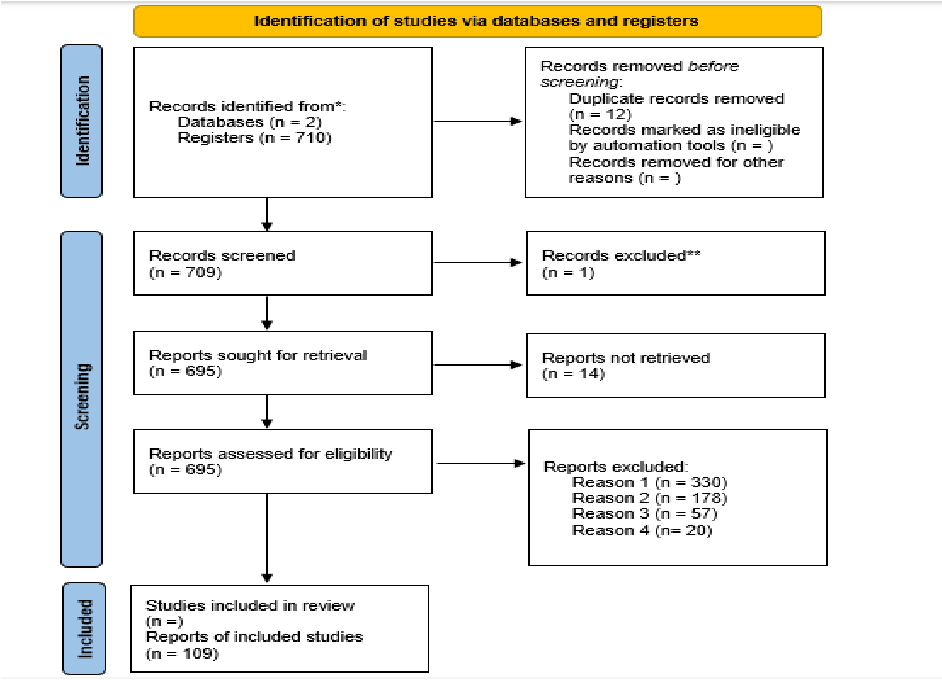


**Figure 1:** Flow diagram PRISMA

**Bibliometric Analysis**

The bibliometric analysis was carried out in three phases (see Figure 2), following this workflow:

1. The respective records were downloaded in Bib format from the Scopus and Web of Science databases. These documents matched the search queries, resulting in a total of 710 documents retrieved.
2. Using Python code, a process was developed to integrate and remove duplicate records, generating a single .bib file with 109 records.
3. Using Python code, the documents were classified according to the journal they belonged to and the quartile rankings assigned to each journal. This yielded a total of 508 documents retrieved from quartiles Q1 and Q2, which are the focus of this article.
4. Using the Bibliometrix tool, the main bibliometric means were extracted, and an analysis of trends related to the study topic was performed.
5. Using the biblimetrix tool, an analysis of the conceptual structure of thematic evolution was developed in its four quartiles.

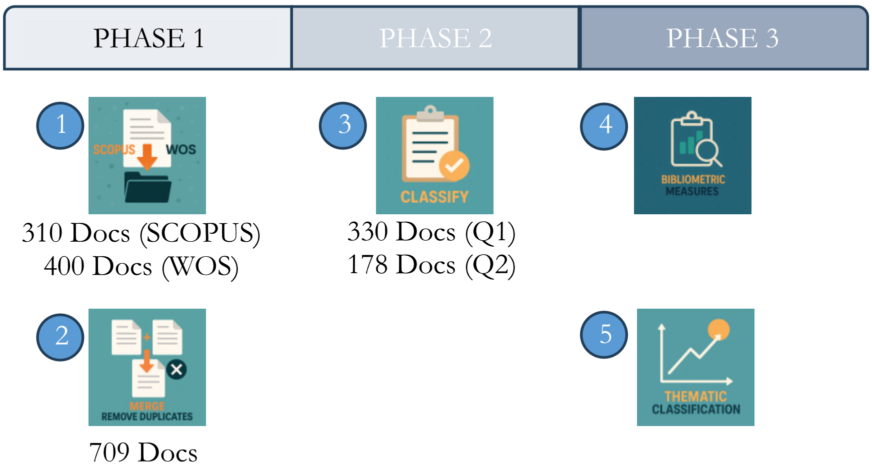


**Figure 2:** Porposed worklow

 

### Computer Applications Used

The table below details the computer applications and versions used for this analysis:

| Software | Version | Use |
|---|---|---|
| Python | 3.14.0 | Code development for document integration and classification |
| R language | 4.5.2 | Core software supporting the Bibliometrix package |
| RStudio | 2025.09.2+418 | Integrated development environment for the R language |
| Bibliometrix | 5.0 | Software tool used to perform bibliometric analysis |

## RESULTS

### Exploratory Analysis of Bibliometric Measures

The bibliometric analysis carried out covered a total of 444 articles published between 1985 and 2025, distributed in 150 journals from the Q1 and Q2 quartiles (See Figure 3). The academic production of the period shows a sustained evolution, reflected in an annual growth rate of 11.21%, which demonstrates the progressive increase in research interest in the analyzed topic.


**Figure 3:** Bibliometric measures

The average age of the documents is 4.86 years, indicating that the field is characterized by relatively recent and constantly updated literature. However, the average number of citations per document is 0.08559, reflecting a still limited impact, possibly attributable to the emerging nature of the area or the significant presence of recent publications with low citation accumulation. The documents collectively list 15,178 bibliographic references. This demonstrates that they possess a strong theoretical foundation and robust intellectual support in knowledge production.

A total of 1,162 indexed terms (Keywords Plus) and 1,789 keywords provided by the authors themselves were identified. The large number clearly shows broad semantic diversity as well as multidisciplinarity in research lines tackled within the corpus.


**Figure 4:** WordCloud

On the issue of authors, a total of 1,374 were identified (see Figure 4), among whom only 24 have published works under individual authorship. Also, 27 documents correspond to the work of a single author while an average co-authorship rate reaches 3.99 authors per article thus confirming the predominance structure working collaborative within scientific community.

 

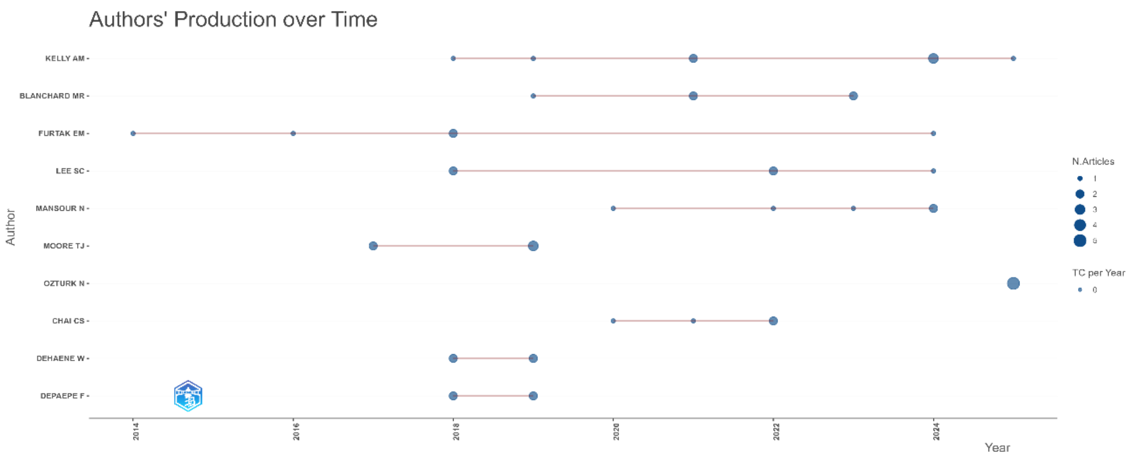


**Figure 5:** Authors' Production over Time
*Note: The 10 authors with the highest scientific output*

**Bibliometric Analysis**

***Thematic Evolution Analysis***

The thematic positioning analysis allowed for the identification and classification of 15 clusters (see Figure 6), based on their centrality (interaction with other themes) and their density (internal cluster development), according to Callon's methodology and community detection using the Walktrap algorithm. The inertia of the distribution of each cluster on the resulting thematic map is then analyzed.

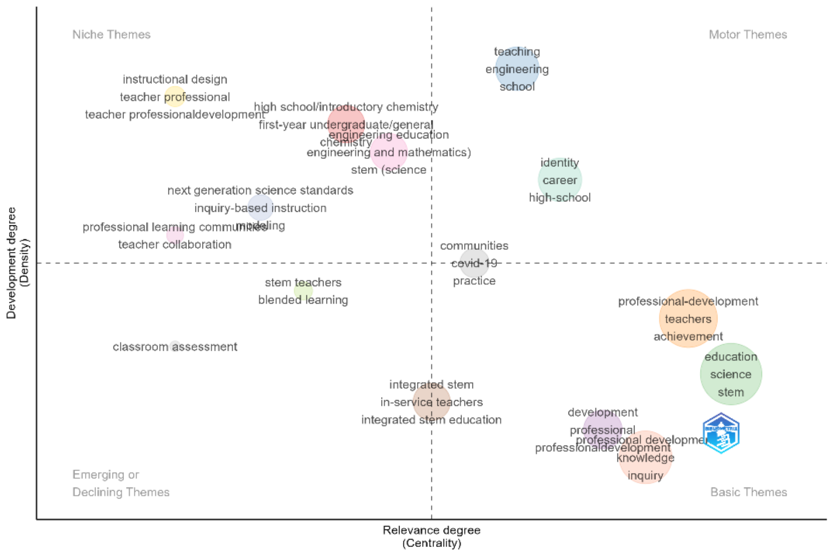


**Figure 6:** Thematic map

***Basic Themes***

The Basic Themes quadrant displays the relationship between conceptual terms defined by authors; in this sense, related research is based on these structures. These basic themes are characterized by high centrality and low density, indicating that they constitute transversal foundations of the field of study, broadly connected to other lines of research, but still undergoing theoretical and methodological deepening. In the area of professional competencies for mathematics teachers in STEM education, the basic themes represent the pillars upon which more specialized approaches are articulated.

Recent literature shows that one of the most recurring basic themes is linked to the integration of educational and digital technologies in mathematics teaching and learning processes. Bibliometric studies and systematic reviews reveal that concepts like educational technology, digital learning, computational thinking, and technological integration always appear as central nodes in the thematic maps hence reflecting their structural role in STEM teacher training [47], [48]. Technological competencies are considered key for teachers to be able to design contextualized interactive learning experiences articulated with current challenges.

 

Another group of basic themes is related to the pedagogical and didactic competencies, mainly those associated with active methodologies, problem-based learning, and interdisciplinary approaches. Recent research emphasizes that these elements are the basis on which mathematical or scientific thinking in STEM contexts can be developed as conceptual support for further innovations in the classroom [49]. Therefore, from this point of view, they are not emerging trends but rather constitute the necessary conditions through which quality teaching can be realized.

The literature also considers the socio-emotional competencies of teachers such as self-regulation, empathy, and responsible decision-making as core themes. These are directly related to the effectiveness of mathematics teaching and student engagement in STEM environments [50]. Not very specialized elements but strongly connected with different lines of research that establish them as fundamentals for teacher professional development.

Technological, pedagogical and socioemotional competencies form the structural base of the field as evidenced by research on basic themes. More advanced approaches are added in later studies concerning professional competencies of mathematics teachers in STEM education, hence reaffirming its cross-cutting and strategic nature within recent scientific literature.

### *Motor Themes*

The Motor Themes quadrant displays the relationship between author-defined conceptual terms; in this sense, related research contains trend publications in this study. These themes are characterized by high centrality and density. They comprise well-developed conceptual cores and are influential within the research field. Concerning studies on professional competencies of mathematics teachers in STEM education, the lines of research dynamism contain impact and scientific projection highlighted by the Motor Themes quadrant.

One of the main motor themes is associated with processes of advanced integration between digital technologies and artificial intelligence in the teaching of mathematics. Artificial intelligence in education, learning analytics, computational thinking, AI-enhanced learning appear at the center of thematic maps revealed by bibliometric/scientometric analyses, reflecting/discussing their apparent strategic role in transforming STEM teaching competencies [51], [52]. Herein emerges that mathematics teachers need technical skills but also/data interpretation/personalization of learning/evidence-based pedagogical decision making competencies.

A further key driving force is the creation of new learning environments and the application of active, technology-supported methodologies such as problem-based learning, simulation, and use of augmented and virtual reality. These areas are both highly theorized and developed empirically, besides being closely allied with other fields of education. Hence, their impact on STEM teacher education is large [53], [54]. The pedagogical competence of mathematics teachers is a key factor for effective implementation and sits at the core role.

Another huge area of research is teacher education and professional development projects. These mostly target higher education by analyzing institutional policies, training models or strategies for the professional development of teachers to adjust to the challenges that are now hot in STEM education [55]. The research discovers an emerging trend toward a comprehensive concept of teaching competence which includes three integrated components: subject knowledge, pedagogy, and technology.

The Motor Skills quadrant reflects the most mature and scientifically relevant trends in research on professional competence of mathematics teachers in the STEM fields. There is a change highlighted here, within the trends of research itself towards instructional innovation, artificial intelligence for education ,and ways to fortify and update teachers through development strategies.

### *Niche Themes*

The Niche Themes quadrant shows the nature of conceptual terms as their writers define them. Trending publications in this area belong to related research. Such themes are high in density but low in centrality; therefore, they represent well-developed internal lines of research still modestly connected to the main core or major thrusts of the field. In works dealing with professional competencies for mathematics teachers in STEM education, niche themes correspond to particularized approaches that are increasingly attracting interest among the scientific community.

Recent text emphasizes niche themes as studies on the development of teachers' socio-emotional competencies which include self-regulation, pedagogical empathy, and responsible decision-making in complex educational environments. Such studies are becoming increasingly theoretically and methodologically sophisticated despite the fact that they are still relatively less articulated with other main lines of research in the STEM field [56]. However, the internal consolidation of these studies indicates a great possibility for the fusion within wider approaches to mathematics teacher training.

Another set of niche themes relates to the use of immersive technologies and particular applications of artificial intelligence aimed at specific educational contexts, such as personalized learning or support for certain groups of students. Recent studies reveal that there is a high level of conceptual development in these lines of research, but practice remains restricted to particular scenarios hence its classification as niche themes within the thematic map [57], [58]. However, steady increase registers toward an eventual explosion into the core area.

Similarly, studies focusing on specific training for teachers in new areas-such as the integration of sustainability, ethics, and advanced technologies in mathematics education-are considered niche themes. Though still rather peripheral when counted among the number of papers that have addressed them directly or explicitly, these high-coherence internally binding emerging scientific output lines are steadily increasing volumes of research literature trends with potential to become core theme trends [59], [60].

The Niche Themes quadrant reflects certain new and specific interests that are gradually expanding regarding the research on professional competencies of mathematics teachers in STEM education. An explanation based on their evolution is provided to show how currently small approaches can become major ones both in the short term as well as long run through integration with other established areas of this field.

***Emerging or Declining Themes***

The "Emerging or Declining Themes" quadrant shows the relationship between conceptual terms defined by authors. In this sense, the related research includes publications that have lost interest or are projected to become more prevalent in this field of study. From a bibliometric perspective, these themes are characterized by low centrality and low density, indicating weak articulation with the core concepts of the field and limited or unstable development in recent literature on teaching competencies in STEM education.

This quadrant includes research linked to pedagogical transitions forced by specific circumstances, such as emergency remote teaching resulting from the pandemic. Although these studies provide relevant evidence on the challenges teachers face in sustaining the development of practical skills and student motivation in virtual environments, their contextual and temporal focus limits their projection as a consolidated trend in STEM mathematics teacher training [51]. The progressive loss of centrality of these themes is explained by the return to more stable hybrid models.

Likewise, research focused on teachers' perceptions of blended learning within the framework of the Fourth Industrial Revolution offers relevant contributions to understanding technological barriers and professional development needs; however, its descriptive and contextual emphasis limits its integration with specific didactic frameworks for mathematics teaching, thus reducing its structural impact in the STEM field [52] . These lines of inquiry appear to be emerging, but have not yet achieved sufficient conceptual depth to become established.

Other studies in this area address transversal competencies such as job satisfaction and teacher self-efficacy, particularly in contexts of linguistic diversity. While these factors influence the retention and performance of STEM teachers, their treatment tends to remain at a general level of organizational analysis, without a direct and sustained link to mathematical teaching competencies, which explains their low thematic focus [61].

Finally, research on assessment in CLIL contexts, while methodologically sound and highly specialized, focuses on the intersection of language and content, which limits its direct application to the core STEM mathematical competencies, keeping it as an emerging line of inquiry with a specific disciplinary scope [62].

Generally, the Emerging or Declining Themes quadrant reflects content that has not yet consolidated structural relevance or decreasing trend in the dominant discourse on professional competencies of mathematics teachers in STEM education. Some approaches, however, may re-emerge if more explicit integration with didactic, assessment and formative models specific to the field of STEM mathematics is provided.

## DISCUSSION

A bibliometric analysis shows that research on (STE(A)M) education and math teacher professional competence has become an accepted area of research and is gaining increasing attention by the end of the period under study. This provides evidence of strategic importance and scientific validation for the literature analyzed since most research results are published in the top 25% journals. The trend confirmed a previous study to state that there is increasing research attention on STEM teacher professional development concerning digital transformation as an interdisciplinary challenge.

The results of this analysis support the significant trend toward collaborative work. Research on competence in STEM teaching is mostly undertaken from an interdisciplinary perspective and within already established academic network structures. This, therefore, reflects not only the complexity inherent to the STEM/STEAM model itself but also that implementation brings together pedagogical methods, technological knowledge, and content-specific expertise supposed to be effectively integrated into mathematics education.

The analysis undertaken on the development of themes clearly exposes the hierarchical structure of mathematics teacher professional competence. The results expose two core themes in the conceptual network: technological competencies and pedagogical competencies that shape the subject area. As existing literature indicates, this makes the effective integration of educational technology and proactive teaching methods no longer a marginal emerging trend, but a fundamental prerequisite for STEM mathematics instruction.

Furthermore, in the most mature and core areas, research focuses on topics such as educational artificial intelligence, learning analytics (computational thinking), and teachers' continued professional development. These capabilities are redefining the competence of mathematics teachers: shifting from a traditional emphasis on subject-matter knowledge mastery to a teacher image capable of designing innovative learning experiences, interpreting educational information, and making evidence-based instructional decisions. This trend can be explained by changing expectations of student competence, particularly at the level of.

The analysis further brings to light a few highly developed but not yet core areas within this field. Among them are teachers' socio-emotional competence, personalized learning through new technologies, and the integration of ethical and sustainability principles in mathematics education. Their current status hints at possible future development and consolidation of the discipline provided that clearer links can be established between them and the dominant directions of STEM education.

However, research that focuses on specific contexts or is primarily descriptive shows less thematic stability. This reflects the dynamic nature of the field and underscores the need to construct comprehensive educational frameworks that connect these approaches to the teaching and assessment capabilities specific to mathematics education in STEM fields.

The findings support the first research hypothesis presented in the introduction: bibliometric analysis helps identify and clearly describe the challenges facing STEM mathematics teacher competence development (H1). By outlining and elaborating on the professional competence framework for STEM mathematics teachers at different educational levels (higher education and secondary education), this paper, to some extent, overcomes the fragmentation problem of other authors' research methods mentioned above. This paper considers the structured understanding built from quantitative descriptive results from scientific publications as one of the many challenges: how to link and integrate institutional guidelines with individual initiatives? The study also identified emerging needs for artificial intelligence applications in education. Bibliometric methods also helped identify gaps and thematic imbalances in professional development, particularly in creativity, assessment skills, and socio-emotional competence (competencies that remain underdeveloped in high-level literature). In this context, the findings confirm that STEM (science, technology, engineering, and mathematics) is an effective tool for trend analysis. Challenges should be identified, and mathematics teacher professional development should be aligned with the needs of current STEM education.

## CONCLUSION

This study systematically analyzes the current state of research development and professional competence enhancement among mathematics teachers in the STEM/STEAM field. The study uses bibliometric methods, based on high-level literature indexed in Scopus and Web of Science. The results demonstrate that the research field continues to grow and consolidate. Specifically manifested in increased research output, a concentration of publications in Q1 and Q2 journals, and the emergence of collaborative research models.

The conceptual structure and themes developed strongly leading to the core elements of this research field. Technological competence and pedagogical skills are structurally based on STEM mathematics teacher education found by conceptual structural analysis meanwhile artificial intelligence in education, learning data analysis, computational thinking application, and continuous professional development emerge as strategic trends established through thematic developments. Therefore, findings show a shift in teacher education models from purely subject-oriented approaches to comprehensively integrated methods that amalgamate mathematical content with instructional innovation and educational technology.

The study identifies certain emerging professional areas within teachers' socio-emotional competence, personalized learning, and ethical and sustainable development oriented mathematics instruction that are still under-researched. The presence of such themes implies the inadequacy of traditional competency models in framing the requirements for a complex and dynamic educational environment.

The results prove that bibliometrics is a highly effective research method. This, therefore, means that its application should not only be limited to describing academic publications but also applied in understanding the development, prioritization, and transformation of mathematics teachers' professional competence in STEM subjects. The study has tested the hypotheses and provided pertinent empirical evidence on which academics and pedagogy in the STEM fields can base their decisions.

 

## IMPLICATIONS FOR FUTURE RESEARCH

The bibliometric analysis showed trends, emerging themes and research gaps in the development of mathematical competence for STEM teachers, it also noted the need to better understand structures beneath this scientific dynamic. In such context, results pose empiric support on recognizing priority research areas that still lack further -and deeper- qualitative inquiry; studies attempting to clearly describe by means of systematization the dynamics between identified terms and conceptual structures lying underneath.

Future studies may particularly apply qualitative and mixed methods, for example, detailed interviews, case studies, and content analysis on how technological competence, pedagogical competence, creativity, and socio-emotional competence are developed and demonstrated in actual teacher education and classroom practice. Thus,[1] researchers will be able to explain the educational processes responsible for these trends in addition to making bibliometric observations.

Detailed comparative studies at different levels of education, regions, and types of institutions to find similarities and differences in mathematics teacher training within STEM education are suggested. Changes in pedagogical competence over time and with technological as well as curricular changes can be analyzed through long-term studies.

In the future, research can apply advanced techniques of analysis such as semantic network analysis, concept modeling, and AI-supported text mining for better interpretations of results from bibliometrics in linking them to existing theoretical frameworks. This would assist in forming a strong model regarding mathematics teachers' professional competence with academic as well as practical impacts on research related to STEM/STEAM.

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