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Research article

Research hotspots and development trends of model and modelling education research: Bibliometric analysis based on CiteSpace

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A R T I C L E I N F O

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A B S T R A C T

Model-based learning and teaching are vital for addressing real-world challenges and are gaining research traction. This study, employing CiteSpace, analyses 583 articles, uncovering trends in authors, regions, and highly cited documents. Noteworthy focuses include learning achievements, technical support, and teaching approaches. Keyword analysis emphasises thinking cultivation and interdisciplinary integration. The study discusses current and future developments in modelling and modelling education research, particularly in learning evaluation and teacher professional development. Offering an international perspective, this analysis provides stakeholders with valuable insights. In summary, model-based learning's growth and influence are evident in the identified trends and future directions, guiding the field toward effective teaching strategies and solving complex problems. This research contributes to the broader understanding of modelling education's dynamics, facilitating informed decision-making for educators and policymakers.

1. Introduction and background

The unprecedented transformations wrought by technological advancement, the explosion of knowledge, and globalisation are reshaping the lives of individuals worldwide. In the face of increasingly challenging circumstances, there is a greater imperative than ever for the public to possess scientific literacy, enabling us, as responsible citizens, to take informed actions to address these challenges effectively [1]. This imperative is particularly pertinent for science educators, as school-based instruction fosters scientific literacy among youth [2]. Indeed, for decades, scientific literacy has been regarded as a primary objective of science education [3,4]. Current perspectives posit that scientific literacy encompasses understanding scientific concepts and insight into scientists' methodologies to construct knowledge, including creating and utilising models [1]. Models and modelling (MM) are considered integral parts of scientific literacy [5], illuminating the nature of science [6]. Models have explanatory and predictive power for abstract things, and modelling provides opportunities for students to develop representations. People use them to generate model-based explanations and predictions and then build an understanding of nature [7]. The potential of MM to improve the quality of science learning achievement is increasingly recognised by teachers and policymakers. The science curriculum standards in many regions include constructing and using models as one of the scientific practices [8,9]. The effectiveness of MM in learning and teaching has been supported by many research results, both in subjects such as physics, chemistry, geography, and biology and in other academic segments such as early

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childhood, primary school, secondary school and university [10]. However, research on MM is still a hot topic in science education, attracting more interest and attention from researchers [11]. With the deepening understanding of MM, people find that it increasingly touches, mobilises and trains students' deep cognitive processes, such as reasoning, relational knowledge, argumentation, and systems thinking [12–14]. In recent years, with the in-depth engagement of MM in school education, the discussion on it has become more diverse. We need more apparent research maps and guidelines to help clarify the international development process in this field and point out the development trend and demand of model and modelling education research (MMER). Therefore, this study aims to reveal the current status of MMER and its directions for future research to provide a more comprehensive panorama for educational policymakers and stakeholders, thus contributing more targeted support to developing models and modelling education.

1.1. MMER

In science education, models are simplified representations of phenomena and processes, and modelling is seen as an important practice. Since the 1980s, MM has been applied in teaching and has shown its positive effect on acquiring knowledge more coherently, flexibly and systematically [15]. MM is a scientific practice process that involves constructing, evaluating, modifying, and applying models [16]. Although researchers have classified MM into different categories, they cannot be separated from the basic steps of the modelling process. Such a classification can also be seen as MM with different openness and difficulty, thus presenting different scales or levels in teaching [17]. MM involves students' learning and teachers' instruction. It generally pays attention to understanding models and modelling knowledge and the mastery of modelling practical experience. In other words, science education not only focuses on the positive role of MM as a tool to achieve teaching objectives but also on understanding MM itself as one of the objectives [18,19]. It is also necessary for teachers to master additional pedagogical knowledge about modelling [19]. The opportunities and forms of MM embedded in teaching are flexible, appearing in various learning stages [20–22], in different disciplines [23,24], with multiple carriers [25,26], and combined with other strategies [27,28]. To present the panorama of MMER, we included science education research related to modelling practice into the scope of analysis and tried to obtain the international hot spots and trends.

1.2. Current reviews about MMER

Six published review articles on MMER dynamics and trends have been retrieved (Table 1). Among them, except for Namdara and Shen as well as Shi and Wang, other studies selected a small number of samples, which limited the reflection of the overall development trend of MMER. These four articles focused on introducing the development of MMER from a particular aspect, such as teacher education, modelling ability, physics education, or within a specific region. Namdara and Shen, as well as Shi and Wang, selected enough samples which were distributed before 2013 and 2017, respectively. However, MMER has developed rapidly in recent years, so finding the latest frontier for academic reference in these two articles is difficult. Namdara and Shen focused on the modelling-oriented assessment of K-12 students and excluded the college students or K-12 teachers, nor did they include other dimensions of modelling education. Shi & Wang did not introduce the research method, and few data were reported to reflect the development trend of MMER. Besides, their discussion was centred on the modelling teaching of chemical education in a particular region. Therefore, these six articles lack an international perspective on analysing the MMER trend, which is of limited reference value to a wide audience. MMER has developed into a broad and diverse field, and its trend analysis needs higher objectivity and comprehensiveness. However, the research methods used in the above articles cannot meet the needs. This study seeks to provide an unbiased and comprehensive look at MMER trends.

Compared with the systematic literature review, bibliometric analysis can give researchers a broader picture. In systematic literature review articles, researchers often carry out content analysis and theme analysis manually, which belongs to the category of qualitative research. Therefore, it is difficult to avoid the interpretation bias caused by the researcher's different academic backgrounds and position research positions [31]. Bibliometric analysis can systematically collect, organise and summarise many pieces of literature in the international scope through algorithms-based statistics. This method can realise quantitative analysis and ensure the objectivity and comprehensiveness of research. By analysing the fundamental indicators such as the change of the subject field, citation status, author influence, article influence, and publication year, bibliometric analysis can evaluate the quality and reliability of the research while minimising the impact of subjective factors caused by the constructed interpretation from the researcher [32].

To sum up, it can be found that MM has received sufficient attention from science education policymakers and stakeholders, which makes it play a key role in school education in promoting students' cognitive development and academic achievement. The development of educational policies related to MM depended on the evidence accumulated by researchers over the years. They have

Table 1
Research on MMER trends.

Authors	Database	Number of documents	Year range	Methods used
Benzer and Ünal (2021)[29]	Science education journals in Turkey	71	2002–2019	inductive
Campbell et al. (2015)	Four journals from SCI-E and SSCI citation databases	81	2001–2011	deductive & inductive
Liu and Sun (2022)	Five journals from SSCI citation databases	62	2010–2021	inductive
Namdara and Shen (2015) [30]	ERIC	153	1980–2013	inductive
Nicolaou and Constantinou (2014)	Physics education journals in Scopus	23	1991–2013	inductive
Shi and Wang (2019)	Seven journals from SCI-E and SSCI citation databases	1920	2007–2017	N/A

diversified discussions on MM-based teaching and learning, showing a vigorous development trend. Rich research and discussion often allow science education practitioners to understand specific aspects of MMER, but it isn't easy to understand the overall picture of it. A comprehensive introduction to MMER is required to address this gap. However, no previous studies on MMER reviewed the overall picture of MMER worldwide based on a large sample size. Therefore, this study used the bibliometric analysis method to carry out a systematic analysis of MMER. Research questions to be resolved as follows:

(1) What is the primary distribution MMER, including the main contributing author, country/region and institution, and highly cited documents? What are the characteristics of their distribution?
(2) What are the hot spots of MMER?
(3) What are the future trends of MMER?

2. Methods

The details of the data sources, search criteria, and analysis methods will be presented in the following parts of this section.

2.1. Software and tools used in the analysis

The data for this study were sourced from the Web of Science (WOS), a representative database of citation data encompassing a broad range of interdisciplinary peer-reviewed research publications in both education and STEM disciplines [33]. To ensure the quality of literature analysis, this study exclusively includes publications from the Science Citation Index Expanded (SCIE) and the Social Sciences Citation Index (SSCI), two core databases within the WOS platform. SCIE covers over 9000 authoritative academic journals in the natural sciences, while SSCI includes more than 3300 influential journals in the social sciences. Utilising data from SCIE and SSCI guarantees the quality and quantity of foreign language literature.

The primary tool for bibliometric analysis in this research is CiteSpace (6.1.R6) application software. This software relies on co-citation analysis theory and pathfinding network algorithms to visually depict scientific knowledge's structure, patterns, and distribution as a knowledge graph. It is a vital tool for visual bibliometric analysis [34]. Compared to other bibliometric analysis software such as VOSviewer and Bibliometrics, CiteSpace was selected as the preferred analysis tool for its comprehensiveness, analytical

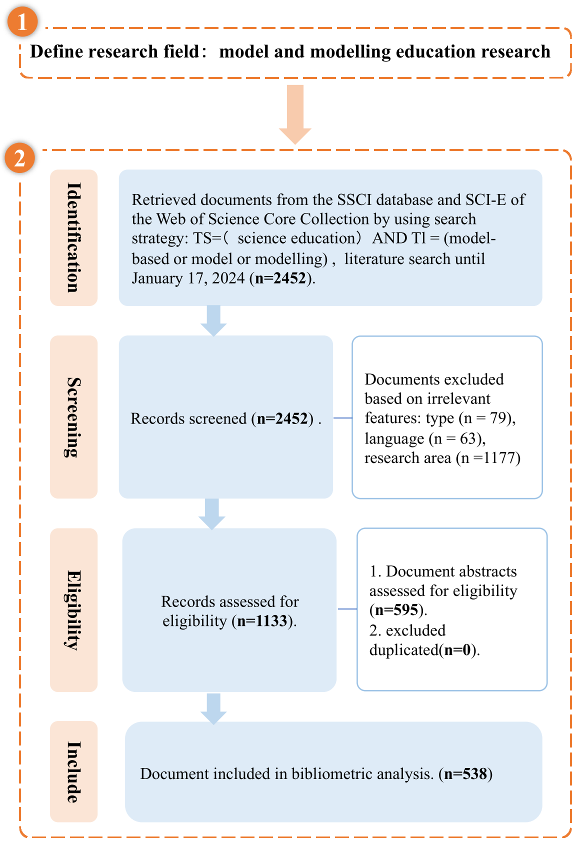

Fig. 1. Flow diagram of PRISMA methodology.

consistency, and user-friendly interface [35].

2.2. Data exploration and plan

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (please note that the authors only followed the steps in scrutiny and did not conduct a systematic literature review as per PRISMA methodology). The details of screening and eligibility are presented in Fig. 1. The comprehensive reporting based on the PRISMA template allows readers to assess the applicability of the methods, thereby evaluating the accuracy of the study's conclusions [36].

To identify articles relevant to our research topic, we initially employed the search strategy: TS= (science education) AND TS= (model or modelling), conducted within the "Topic" field, resulting in 20,080 documents. However, most of these documents needed more relevance to our study. Therefore, we adjusted our search strategy based on existing review studies to TS= (science education) AND TI=(model-based or model or modelling), focusing the search on the "Title" field to ensure relevance to the themes of modelling and model-based education. This search was conducted on January 17, 2024. To ensure the accuracy and consistency of our dataset, we conducted the following data-cleansing steps:

1. We only utilised categories provided by WoS, such as "Education scientific disciplines" or "Education educational research," to ensure relevance to our research topic.
2. Only journal articles were retained, while conference papers, books, and book chapters were excluded, as suggested by Freire & Nicol [37] and Wang et al. [34], as journal articles hold the highest academic value.
3. Only entries with English as the language of publication were retained to ensure consistency in the dataset's language, considering potential differences in vocabulary and citation conventions across languages.

A total of 1133 articles were retrieved. To further confirm the eligibility of selected studies, all articles underwent thorough manual screening by researchers. All two researchers reviewed the titles and abstracts of the included articles to verify compliance with inclusion criteria and excluded irrelevant articles focusing on teaching models, statistical models, evaluation models, etc. Ultimately, 538 articles meeting the established criteria were identified, with a publication record starting from 2006. These records were exported in "plain text" format, with the document type "full record and cited references." Each article record includes title, authors, institutions, abstracts, keywords, publication dates, journals, and references. These articles were designated for subsequent bibliometric review and in-depth analysis.

2.3. Data analysis

In accordance with Chaparro and Rojas-Galeano [38], bibliometric assessment involves two stages: dynamics analysis and structure analysis. Dynamics analysis considers the growth and distribution of publications and authors' timelines, while structure analysis includes co-occurrence networks, thematic maps, and collaboration and co-citation networks. Using CiteSpace software, we analysed dynamics and structure, including the authors, publishing institutions, and countries, and detailed analysis of highly cited papers of the selected articles. We imported the selected 538 documents into CiteSpace from January 2006 to January 2024, with a time slice set at one year and PathFinder as the pruning method while keeping the remaining options at default settings. The CiteSpace data visualisation presents the relationships between the information in the literature by forming nodes and lines in the graph.

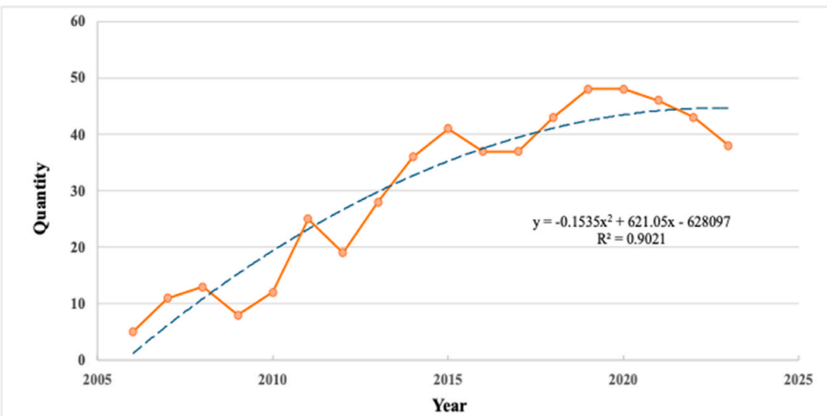

Fig. 2. Annual distribution of the number of articles issued.

3. Results

3.1. Analysis of basic information on MMER

3.1.1. Annual distribution of publications

Publication and citation trends serve as key performance indicators for assessing the progress of a discipline [39]. The distribution of MMER articles over the years is depicted in Fig. 2. Before 2009, the annual publication volume hovered around ten articles, indicating that MMER was still in a developmental phase. From 2010 to 2013, the average yearly publication volume increased to around 20 articles, suggesting an uptick in research engagement. Significantly, from 2014 to 2023, relevant studies have had a sustained upward trajectory, consistently exceeding 30 articles annually. Particularly noteworthy is the period from 2018 to 2022, where the literature count stabilised at 40 articles or more. The second-order polynomial fit curve achieves an R-squared value of 90.21 % (R-squared values range from 0 to 1, with higher values indicating better model fit to the data and lower values indicating poorer fit). This high R-squared value signifies that MMER is becoming a prominent research trend in science education.

3.1.2. Active authors and their collaboration

A collaborative knowledge graph unveils the collaboration network among authors in a specific field [40]. Fig. 3 illustrates the academic cooperation among authors engaged in MMER, specifically highlighting authors who have published three articles or more. The graph reveals the existence of four distinct academic research teams, indicating a trend toward small-scale author collaboration. These four research teams exhibit relatively close cooperation in the field of MMER. The graph comprises 439 nodes and 352 connecting edges, with a network density of only 0.0036. This suggests that, from 2006 to 2023, a considerable number of authors focused on MMER, but the collaboration among authors was limited, and there were fewer core authors. Drawing insights from existing MMER reviews, these four research teams reflect the primary core content of current MMER research. The team led by Becker Nicole M primarily focuses on students' epistemic ideas about models and modelling, and Becker Nicole M, the most prolific author, has published six articles. The team led by Astrid M.W. Bulte concentrates on transforming authentic modelling practices into meaningful contexts for learning. The team led by Cory Forbes is primarily engaged in exploring the role of scientific modelling in students' conceptual development. Lastly, the team Tom Bielik led mainly delves into modelling competence research.

3.1.3. Distribution of country/region and institution

The analysis of international collaboration in MMER reveals relationships between different countries and their impact on the field [41]. Fig. 4 presents the contributions and collaborations in the MMER field from 2006 to 2023. The analysis indicates that 55 countries/regions have participated in MMER-related research. Geographically, the United States dominates MMER research, accounting for nearly 40 % of the studies. This highlights the U.S.'s prominent position and influential role in shaping the direction and progress of MMER, emerging as a central hub for research collaboration. This dominance is not surprising, considering that Professor

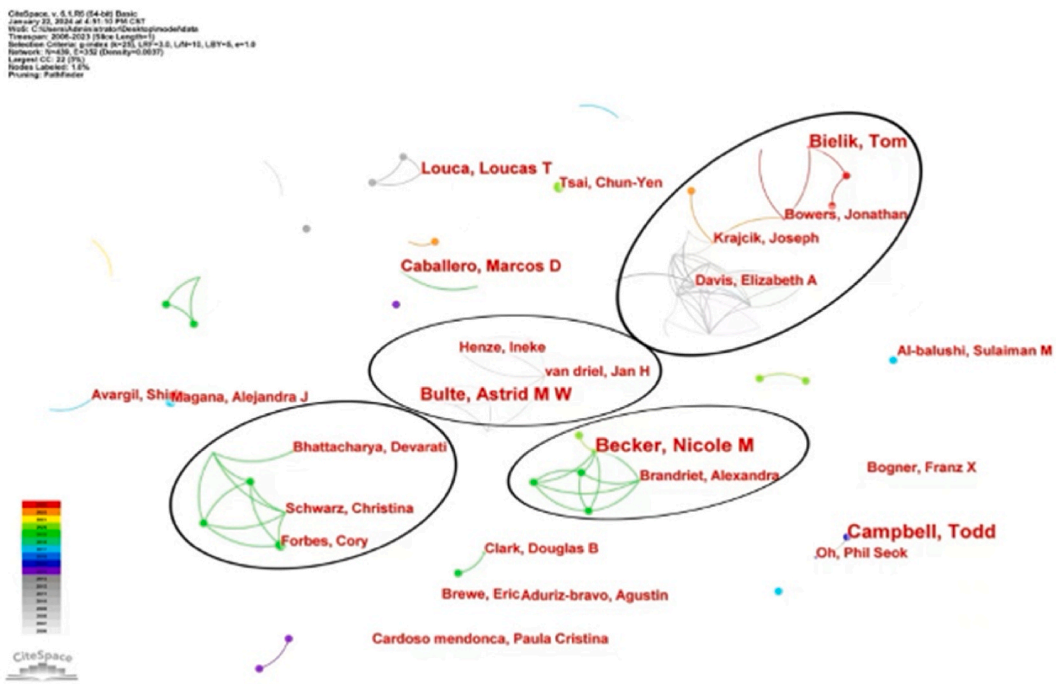

Fig. 3. Authors' collaboration network map.

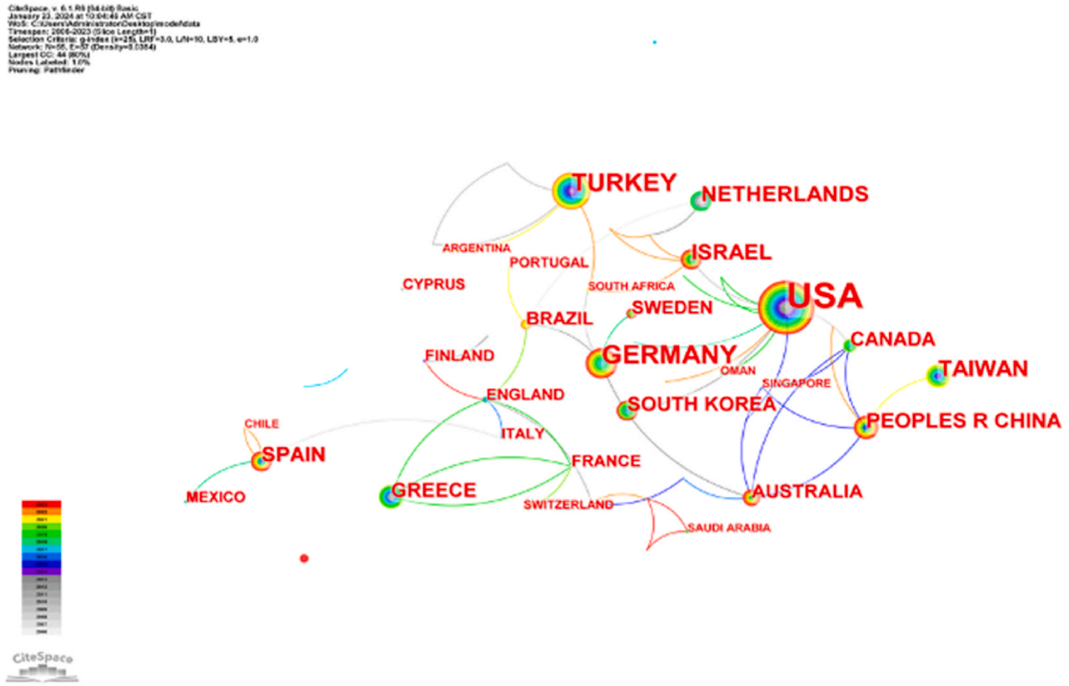

Fig. 4. The country of origin of the article.

Hestenes, a key figure in science modelling education theory, originated from Arizona State University in the United States. Professor Hestenes guided his students in developing the concept of science modelling education, marking the inception of modelling education theory [42,43]. The subsequent rise in research on modelling education can be seen as a microcosm of nearly three decades of science education research in the U.S., leading to one of the most successful teaching reform experiments in U.S. history [44].

Following the U.S., Germany and Turkey emerge as significant contributors to MMER, with 46 and 44 publications, respectively, making them the only countries, apart from the U.S., with publication counts exceeding 40. The institutional collaboration network graph (see Fig. 5) reveals that 333 institutions globally have contributed to MMER from 2006 to 2023. Nodes in the co-occurrence network are primarily regional clusters and isolated nodes, indicating low connectivity. While multiple small groups with diverse

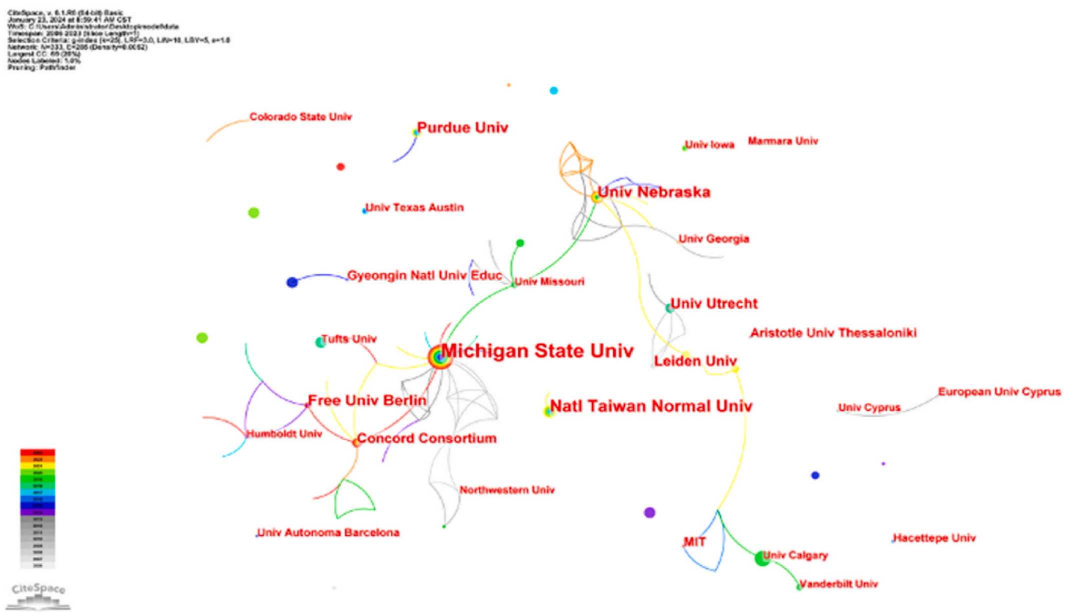

Fig. 5. Major research institutions.

backgrounds have formed within this research field, significant large-scale cooperation and interaction between institutions in different regions are yet to be observed. Michigan State University and Nebraska University are central nodes with high productivity and significant collaborative connections, forming key MMER hubs. Their research encompasses the impact of modelling education on students and teachers and investigations into modelling education with technological support.

A statistical analysis of the top 10 countries/regions and institutions (see Table 2) in terms of publication count reveals that the critical role of the U.S. in MMER is mainly due to its high publication frequency and essential research collaborations. Collaborative efforts and partnerships among researchers and institutions within the U.S. have significantly contributed to the growth and development of the MMER field. In summary, the analysis of international collaboration in MMER underscores the field's global nature and the researchers' collective efforts worldwide. While the United States maintains a core position, the contributions from other countries reflect a widespread interest and collaborative initiatives in exploring the potential of MMER in science education. Existing international collaborations have facilitated knowledge exchange, provided cross-cultural perspectives, and enriched the outcomes of MMER.

3.1.4. Highly influential literature of MMER

Co-citation analysis can be used to identify the literature that highly influenced other research in science education. Those highly co-cited studies serve as a crucial knowledge foundation for research on its related area. Identifying them helps retrospect previous knowledge achievements and provides a basis for a dialectical view of knowledge development. Table 3 outlines the literature in MMER that has demonstrated substantial impact. The highlighted literature covers various topics, including discussions on the epistemology of MM, the roles of students and pre-service teachers, relevant theories, and methodologies. The high citation count of Christina Schwarz's work indicates a considerable focus on modelling literacy among researchers. Influenced by the Organization for Economic Co-operation and Development "Definition and Selection of Competencies: Theoretical and Conceptual Foundations" project, developed countries have, over the past decade, begun constructing their national core competency systems for students within its framework. Due to the widespread recognition of scientific modelling in science education and its incorporation into curricular documents in many countries, it is considered a vital component of core scientific literacy. Among the numerous studies on modelling literacy, developing the level model for constructing modelling competence has been a significant advancement. Schwarz's teamwork on the impact of fifth and sixth-grade students' learning, emphasising models' generative functionality and understanding models' revisability, has played a pivotal role. Additionally, the team led by Bamberger extended the research to middle school students, exploring aspects such as the transfer of modelling performance between knowledge domains under the framework of learning progressions. This expansion not only broadened the scope of the study to include middle school students but also served as a complementary description to the original level model [45].

3.2. Analysis of research hotspots in MMER

Keyword co-occurrence networks offer insights into a particular field's hotspots and core research topics [46]. Analysing the keyword co-occurrence in MMER allows for exploring active research areas and knowledge structures. Fig. 6 illustrates a keyword co-occurrence network with 473 nodes and 993 lines, representing keywords with frequencies exceeding 10. The nodes correspond to keywords, and the larger, closely connected nodes such as "science," "education," "science education," and "knowledge" reflect common research focus areas. The study conducted document co-citation network clustering to further investigate the relationships between high-frequency keywords. Clustering names were derived from the cited literature's titles, keywords, and abstracts using the log-likelihood rate (LLR) algorithm. Each node in the clustering represents an individual referenced document, with its size and colour reflecting its frequency and timing of citation. Two metrics, Modularity (Q) and Silhouette (S), were employed to evaluate the clustering effect. A higher Q value indicates better network clustering, with a range of [0, 1], where $Q > 0.3$ signifies a significant network structure. S measures the homogeneity of the network, with a value closer to 1 indicating higher homogeneity. A Silhouette of 0.7 suggests high reliability in the clustering result. In Fig. 7, $Q = 0.722$ and $S = 0.882$, indicating a significant clustering structure and high reliability. To maintain cluster clarity, the figure displays 11 clusters with a co-occurrence number exceeding ten and a Silhouette greater than 0.7. After thoroughly examining the information within each cluster, a secondary merge was performed, resulting in three prominent MMER themes (see Table 4).

Table 2
Top 10 countries/regions and institutions for publications in the field of MMER.

Number	Country/Region	Count	Number	Institution(Country/Region)	Count
1	USA	220	1	Michigan State University (USA)	22
2	Germany	46	2	Natl Taiwan Normal University (Taiwan)	13
3	Turkey	44	3	University Nebraska (USA)	11
4	Taiwan	27	4	Purdue University (USA)	10
5	Israel	23	5	Free University Berlin (Germany)	10
6	Netherlands	23	6	Leiden University (Netherlands)	8
7	Spain	21	7	University Utrecht (Netherlands)	8
8	China	20	8	Concord Consortium (USA)	7
9	South Korea	18	9	Aristotle University Thessaloniki (Greece)	6
10	Greece	17	10	MIT (USA)	6

Table 3
Highly influential literature in science education research.

Number	Authors	Co-cited frequency	Year	Title
1	Christina Schwarz	650	2009	Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners
2	Phil Seok Oh	174	2011	What Teachers of Science Need to Know about Models: An overview
3	Richard Lehrer	155	2012	Seeding evolutionary thinking by engaging children in modeling its foundations
4	Loucas T. Louca	124	2012	Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions
5	Eric Brewe	116	2010	Toward equity through participation in Modeling Instruction in introductory university physics
6	Eric Brewe	113	2009	Modeling instruction: Positive attitudinal shifts in introductory physics measured with CLASS
7	Ineke Henze	109	2008	Development of Experienced Science Teachers' Pedagogical Content Knowledge of Models of the Solar System and the Universe Ineke Henze
8	Julia Gouvea	96	2017	'Models of' versus 'Models for' Toward an Agent-Based Conception of Modeling in the Science Classroom
9	Eve Manz	94	2012	Understanding the codevelopment of modeling practice and ecological knowledge
10	Christina Schwarz	93	2009	Developing preservice elementary teachers' knowledge and practices through modeling-centred scientific inquiry

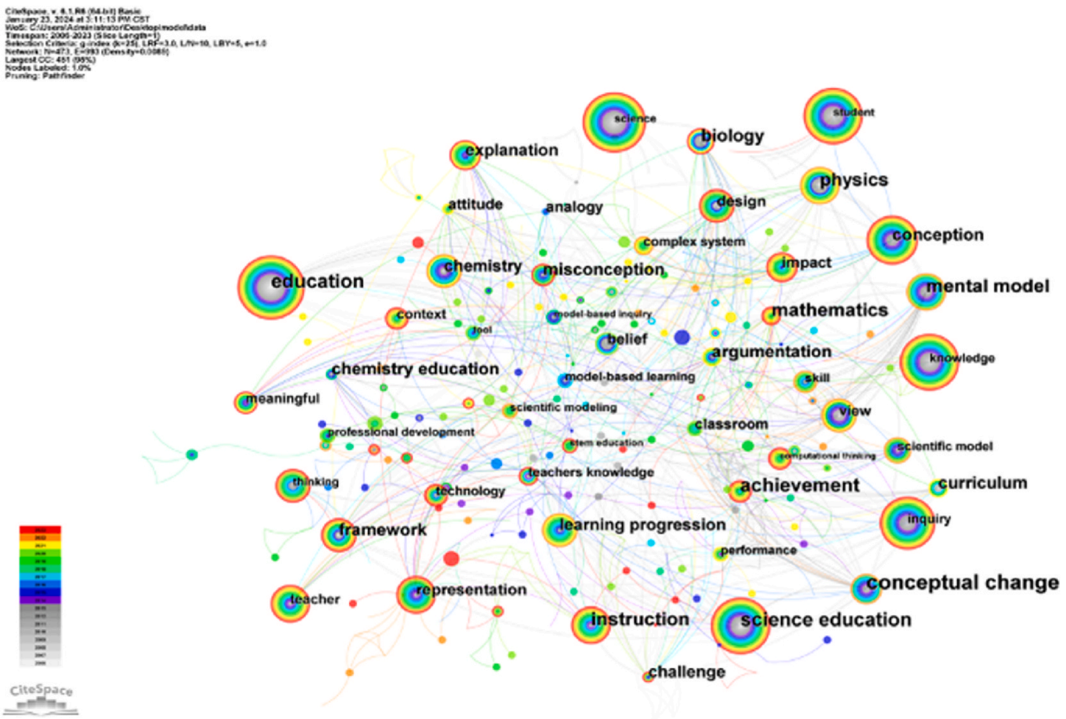

Fig. 6. Keyword co-occurrence analysis.

3.2.1. Theme 1: The impact of MM on student achievement

MM can improve students' science learning achievement, generally manifested in conceptual change, problem-solving ability, and science process skills. From childhood, humans naturally interpret the world as they see it by constructing simplified, intuitive personal theories, that is, building models in our heads [47]. This cognitive characteristic is strengthened after entering school. Thus, learning concepts through constructing and using models has become the focus of research. The task that most naturally engages and supports conceptual change is using various tools to build physical, visual, logical, or computational models representing abstract concepts [48]. For example, Wilkerson-Jerde's and Kamarainen's teams used computers to model microscopic odour molecules' diffusion and macroscopic ecosystems' dynamics, respectively [49,50]. Constructing models allows students to explore the self-organising nature of natural phenomena from perspectives that cannot be experienced with the naked eye. MM functions as a cognitive resource [51], reflecting and regulating people's cognition of abstract things. Thus, MM is a vital teaching and powerful evaluation tool [52]. Developing modelling tasks and model-based evaluation are ongoing topics of interest in science education.

Lee's team found that modelling facilitates conceptual change by supporting problem-solving [53]. The effect of modelling on

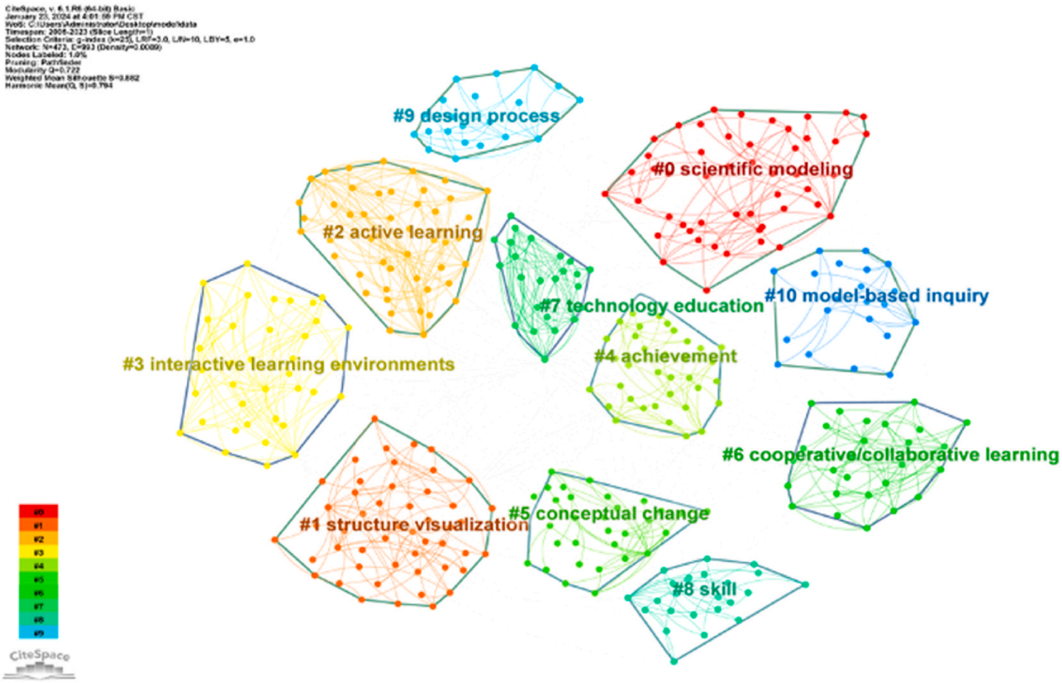

Fig. 7. Clustering of co-words for co-citation clustering.

Table 4
Clustering results and attributed topics.

Cluster ID	Size	Silhouette	Mean (Year)	Top Terms (Log-Likelihood Ratio)	Belonging Subject
0	71	0.741	2015	Scientific modeling	①②③
1	52	0.802	2013	Structure visualisation	①②
2	51	0.788	2015	Active learning	①②
3	48	0.771	2013	Interactive learning environments	②
4	45	0.828	2015	Achievement	①
5	34	0.917	2010	Conceptual change	①
6	33	0.843	2009	Cooperative/collaborative learning	③
7	33	0.882	2015	Technology education	②
8	29	0.828	2017	Skill	①
9	21	0.897	2013	Design process	①②
10	17	0.894	2016	Model-based inquiry	③

①Theme 1: the impact of MM on student achievement; ②Theme 2: the support of computer technology to MM; ③Theme 3: approaches that support MM learning.

conceptual change depends on the learning activities of the problem-solving process, which improves students' problem-solving skills. The students solve problems and balance cognitive conflicts using scientific process skills [54]. Models characterise the spatio-temporal structure and causal relationships in the events through their components and interactions [48]. Therefore, solving problems through modelling will stimulate students' intellectual activities, such as using basic process skills (e.g. observation, classification, measurement, prediction, causal reasoning, control variables, communication, and use of spatiotemporal relations) and comprehensive process skills (e.g. hypothesis, operational definition, experiment, and interpretation of data) [53,55]. Jonassen et al. [48] argued that one reason for the incredible power of modelling is intellectual autonomy. Therefore, the learning activities based on MM are multi-level and multi-faceted, and the impact on learning achievement is comprehensive. It can positively influence the improvement of conceptual, procedural, and metacognitive knowledge through problem-solving [54,56].

3.2.2. Theme 2: The support of computer technology to MM

Computer technology is one of the essential supports for students to create meaningful science models, which is more stable and consistent than support from teachers and peers [57]. Nguyen's team [58] and Xiang's team [59] helped students understand ecosystem dynamics by designing and implementing learning tasks based on computer models. They found that compared to pen and paper or physical forms, computer technology can improve the effectiveness of constructing and using models by facilitating visualisation, evidence-based interpretation, causal reasoning, cross-scale phenomenon correlation, and iterative testing of alternative hypotheses. A model is a structured representation obtained after purposeful approximations and assumptions about the described object rather than the object itself [16]. The more accurate a model is at simulating things, the more complex it is, and the more sources of information need to be integrated to build the model. Jonassen et al. [48] indicated that understanding complex scientific phenomena or solving complex real-world problems through MM may place high demands on working memory, resulting in a high cognitive load. However, the MM supported by computer technology better addresses the challenge of student understanding caused by potentially high cognitive load and low accuracy. Komis et al. [60] reported that learning environments designed based on data logging systems, drawing tools, and virtual and simulation software assist students in negotiating, testing, and refining their mental representations, which are mediated by techniques for creating external representations. For example, Markauskaite's team [25] help students build representations of the carbon cycle with models based on computational agents through direct observation, direct abstraction, generalisation, conceptualisation, and extension. Xiang's team [59] found that computer technology reduces the spatiotemporal limitation imposed by traditional modelling methods, visualises the relationship between data and variables through human-computer interaction, and helps students to conveniently and iteratively carry out reasoning and argumentation based on data patterns. Furthermore, it enables more prosperous and dynamic presentations of structures or sequences so students can easily organise their modelling process and construct coherent sensemaking of core ideas and crosscutting concepts [57]. Modelling practices supported by computer technology are more conducive to students thinking about "how" and "why" questions [58]. Developing MM tasks supported by computer technology and demonstrating their effectiveness are the focus of current research. In this kind of research, researchers pay more attention to the final results and do not track the process of students' thinking, motivation, and belief changes enough during the modelling activities.

3.2.3. Theme 3:Approaches that support models and modelling learning

Currently, two primary research perspectives focus on how to support students in modelling learning. One perspective centres on the design of modelling teaching activities and instructional strategies, offering implementation recommendations. These activities often serve as stages in teaching, either as a review and synthesis of "learned" knowledge or as a means for learning transfer and evaluation. Based on this perspective, researchers Oh & Oh [61] proposed five effective modelling strategies: 1) Exploratory modelling, 2) Expressive modelling, 3) Experimental modelling, 4) Evaluative modelling, and 5) Cyclic modelling. They argue that these five modelling activities reflect how scientists use models in their work, emphasising their equal consideration in science teaching and learning. Subsequent researchers have explored how to embed these modelling teaching methods into classrooms to achieve targeted student learning outcomes, such as conceptual understanding of scientific concepts, scientific practices, and the nature of models and science [62].

The other perspective originates from the process and patterns of modelling, conducting Model-Based Inquiry (MBI), a new iterative and cyclical approach to inquiry-based teaching. This learning method posits that students should construct understanding by engaging in processes like how scientists comprehend the natural world and learn about the nature of science. When applying MBI, students participate in cognitive reasoning activities, constructing or modifying existing models based on phenomena or data patterns from nature or experiments and using models to explain new phenomena and data. Therefore, MBI is considered "model-based thinking," more suitable for teaching in higher cognitive developmental stages than traditional inquiry teaching methods. Attempts to introduce MBI into science classrooms can be traced back to the 1980s, making it a key research area in science education [63,64]. An in-depth analysis of clustering node information reveals that much of the existing research has focused on the application effects of MBI. Some studies also explore the learning characteristics of learners during this process, such as those by Campbell et al. [65], who, based on MBI, investigated key features of dialogue patterns and their instructional functions.

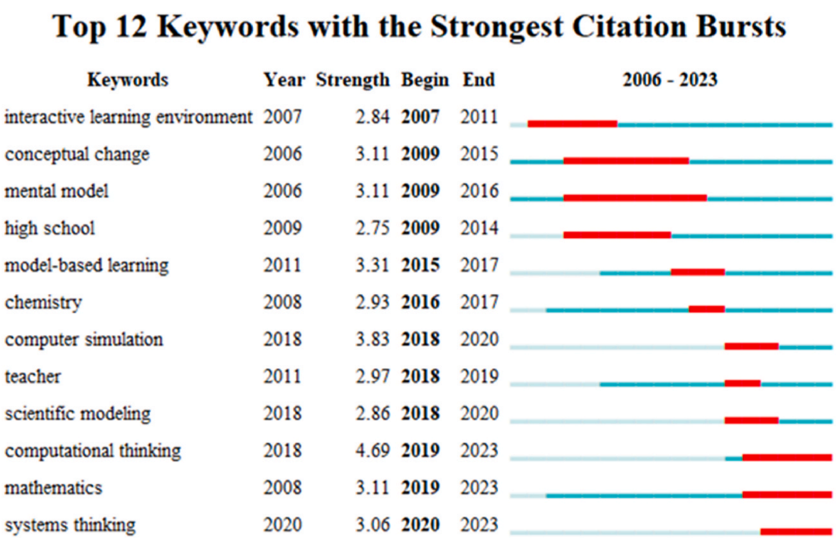

Fig. 8. Top 12 keywords with the most robust citation bursts.

Both perspectives in these studies emphasise the construction of learning environments. Drawing on widely accepted learning theories and explorations in the learning sciences, such as situated cognition theory, metacognition theory, and relevant findings from inquiry activity research, researchers believe that besides cognitive factors, emotional, social, and contextual factors are crucial elements influencing conceptual change in learning. Therefore, efforts are made to create rich learning environments that support the effective implementation of modelling activities in science teaching. The notion of *learning as a social activity* in communities of practice that may leverage model-based learning is prevalent in education. Collaborative-based modelling effectively promotes team reflection, communication, and planning [66].

3.3. Future research trends in MMER

A significant increase in keywords or citations for a particular research topic can indicate its dynamic characteristics [34]. By acquiring keywords that burst with time, the development of a research topic can be roughly identified [67]. Fig. 8 presents the top 12 burst keywords of MMER, and the visualisation presents burst intensity, start and end years, and duration. From 2009 to 2023, keywords such as "conceptual change," "mental model," "model-based learning," "computational thinking," and "system thinking" appeared successively. It shows that the influence of MMER on students has been from conceptual understanding to the cultivation of thinking, and it attaches importance to establishing a systematic perspective. This is consistent with our analysis. As the function of MM was further revealed, its organisational power to teaching became more robust, and the learning achievements gradually changed from single to multiple, which allowed students to think, deconstruct, explain and solve complex problems. From the overall observation of Fig. 8, we found that MMER pays more attention to supporting students' learning processes and outcomes than teachers. MM's benefits to science learning only apply if students are adequately instructed [68]. It indicates that future research should strengthen the support for the teacher professional development of MM.

The burst of a keyword persisting in time represents a research frontier. As can be seen from Fig. 8, "computational thinking," "mathematics," and "system thinking" are the current burst keywords. It indicates that cultivating computer thinking and system thinking through MM, as well as combining MM with mathematics, are the research hotspots of MMER at present. This trend is consistent with the advocacy of integrated learning, which aims to cultivate students' core competencies to adapt to the future society.

In a world where computers are ubiquitous, the demand for computer and systems thinking is on the rise to deal with real problems that are becoming increasingly complex and knowledge-intensive [69]. MM is an effective way to cope with the challenge, as supported by data [13,49]. The role of MM has gone far beyond simple visualisation. For example, Samarapungavan et al. [70] (2023) and Wilkerson-Jerde et al. [50] found that models function more as tools for observing systems, training scientific thinking, and understanding and predicting the general behaviours of the system. Allowing computer technology to aid in problem-solving greatly broadens the depth and breadth of intellectual activity activated by MM. Students will get robust support from more diverse, intuitive, dynamic models in the virtual environment. Although researchers have developed some disciplinary or interdisciplinary modelling tasks to improve students' computer and systems thinking, but such resources are still lacking. In addition, the intellectual activities, emotional activities, and skills involved in computer thinking and systems thinking are rich, so many definitions and discussions exist about them [71]. Future research needs to clarify the conception of computer thinking, systems thinking, and MM and the potential internal relationship between them (which may be two-way) [69] to strengthen the guidance for teaching. Another effort that needs to be made is to help teachers obtain PCK for the three topics, including understanding computer thinking, systems thinking, and MM, and effectively implementing the corresponding teaching.

Another keyword, "mathematics", also intersects with systems thinking, computer thinking, and Rez et al. [72] argued that being well prepared in mathematics not only obtains excellent tools to analyse data, perform calculations, and simulate but also helps to improve organisational and planning skills and analytical and logical reasoning skills. Rachmatullah and Wiebe [73] developed MM tasks integrating mathematics, engineering and science to discuss the impact on computer and systems thinking. The discussion about mathematics and MM is, on the one hand, the mathematical application and, on the other hand, the integration of mathematics and other disciplines in the school [74]. MM plays a key coordinating and organising role in each of these scenarios.

In conclusion, MMER is moving in a more in-depth direction. Of course, the problems and complexities of planning and practical implementation are also inevitable challenges for researchers. As for systems thinking, computer thinking, mathematics, and MM, no matter which one or several elements are used as the background to enhance students' engagement and understanding of the other elements, the broader follow-up research needs to make further efforts at conceptual interpretation, instructional design, and teacher professional development.

4. Conclusions and discussion

From the standpoint of research progress, MMER exhibits an overall upward trend, particularly after 2014, entering a phase of rapid development in MM-related studies. This surge can be attributed to the formal inclusion of "developing and using models" in the Next Generation Science Standards (NGSS) released in 2013 as one of the eight science practices students should engage in. Consequently, MMER has become one of the forefront hotspots in international science education. By analysing the research authors, countries, institutions, and highly cited journals in the MMER field, it's clear that the United States is the leading contributor, with publication volumes that far exceed those of other countries. Reflecting on the developmental history of MMER in the United States can offer valuable insights for countries similarly focused on MMER. Additionally, the co-authorship network graph shows that although the overall network is somewhat dispersed, there is a trend toward small-scale collaboration, indicating that these research groups constitute the significant research forces in current MMER. Analysing high-frequency keywords and keyword clustering graphs, the current research focus in MMER is primarily centred around the impact of MM on students' learning achievements, computer technology support for MM, and approaches to implementing MM learning. By detecting salient terms, the forefront and future research directions in MMER will revolve around the interaction of mathematics, computational thinking, systems thinking, and modelling.

Our results of research hotspots of MMER could suggest to teachers and policymakers in school education how to play the role of MM in promoting teaching and learning and put it into action.MM positively affected students' conceptual understanding, scientific process skills, problem-solving ability, and system thinking and computational thinking. It can be found that the depth and breadth of MM's activation of intellectual activities are increasing. Science teachers can trust MM and apply it to teaching and achieving multiple learning objectives. Given the fruitful support of computer technology for MM, schools should provide opportunities and resources to create technology-based MM learning environments. As mentioned above, the two perspectives of the MM implementation approach allow science teachers to choose different levels and scales of MM learning activities flexibly to support effective classroom teaching. Among them, MBI is promoted for its ability to facilitate further connections between inquiry and scientific content or conceptual models. Yet the relationship between modelling and inquiry is complex, and they need to be combined and adequately ordered to be helpful. Further research is needed to understand better the interplay between modelling and inquiry from the perspectives of teaching and learning sciences. The emergence of the words "computational thinking," "mathematics," and "system thinking" indicate that the function of MM has been deeply revealed as promoting thinking cultivation and discipline integration. However, further research is needed to build a clear conceptualisation, clarify the mechanisms by which these key concepts interact, and develop aligned resources for student learning and teacher professional development.

In our interpretation of MMER research hotspots, we found that MM has been seen as an effective learning strategy and an essential component of academic achievement, often presented as modelling ability. Building modelling competency is recognised as a core skill that should be cultivated across all educational levels [16]. Teaching, learning, and evaluation are inseparable in education, in which the understanding of modelling ability depends on the assessment of it. Thus, assessing modelling competency and its constituent elements is crucial in science teaching, learning, and overall science education. The evaluation of modelling competency has yet to advance to the stage of developing and validating individual measurement scales. The most used tools in current assessments include (a) surveys (open-ended, closed-ended, Likert-type, etc.), (b) interviews (primarily post-intervention interviews), (c) concept maps, (d) models constructed by students (based on computer-based papers), and (e) coding schemes for analysing students' ongoing work (via computer log files and videos) [7]. Typically, these tools are primarily employed for summative assessments before and after instruction. However, excessive reliance on summative assessments may lead to shallow, repetitive, and passive learning experiences for students. Therefore, to evaluate students' learning outcomes more finely, the design of formative assessments is necessary, ensuring students are deeply involved throughout the evaluation process. It becomes crucial to establish a clear theoretical framework for assessing modelling competency to support attempts at formative assessment. In existing research, modelling competency needs a unified definition. Only a portion conceptualised as modelling competency is defined and evaluated among the available theoretical frameworks. Even when investigating specific modelling aspects, researchers often use different definitions, leading to diverse assessment methods. Therefore, the evaluation of modelling ability can be a potential topic for future research, aiming to build a coherent framework for evaluating knowledge, practices, and processes related to modelling, thereby helping to define the sub-dimensions of modelling and construct formative evaluation content.

The results of this study suggest a gap between the rich and imitable methods and resources that MMER has provided for school science teaching and the actual model-based teaching. The current MMER focuses more on students' learning, from which to reflect and discuss the impact of MM and the underlying mechanisms. Although this has some implications for science teachers, it does not mean they can effectively apply MM. If the cutting-edge MMER is expected to benefit more students, it relies on improving teachers' understanding and mastery of MM. Therefore, the development of teacher professional development pathways and resources must also receive more attention from researchers and policymakers. The knowledge framework of MM for teachers covers meta-modelling knowledge, modelling practical experience, and modelling pedagogical knowledge [75]. The current research mainly explores teachers' cognition or attitude towards the first two kinds of knowledge and the current status of implementing MM [76,77]. Even for the research on MM teacher professional development, acquiring the first two pieces of knowledge is the main focus and results [78,79]. Most training groups are pre-service teachers, and the way is to let them participate in and experience the MM like students [80,81]. However, few studies have provided ways to help teachers acquire pedagogical knowledge about MM. With the in-depth research of MM learning, more intellectual activities can be activated, while more challenges will be brought to teachers. Teachers need to consider combining MM with subject knowledge, coordinate these intellectual activities to ensure the smoothness of instructional logic, and try to achieve multiple objectives, including knowledge, ability, emotion and nature of science. Shi et al. [82] have provided an evaluation framework for teaching MM that can be a reference anchor for teachers to deal with these challenges. However, teachers may need more direct support from teachers' professional development resources rather than a theoretical framework to serve as a reference. Future research could guide teachers in designing and implementing detailed and integrated MM-based teaching and, for example, explore ways to support teachers in acquiring pedagogical knowledge of MM-based teaching rather than just an understanding of MM.

This study provides readers with valuable information on the international development status of MMER and reveals research trends and dynamics. But there are still some limitations. Since the research articles included in this study for analysis do not all explicitly identify the level or category of MM, we can only discuss MM as a whole. This increases the granularity of our analysis. In addition, We only analysed articles from the SSCI and SCI-E databases in English. We acknowledge that this approach overlooks articles in other languages and those indexed in other databases, thus limiting the depth and comprehensiveness of our analysis. Understanding increasingly specific research pathways requires closer scrutiny of literature and conducting more in-depth research analysis based on this foundation. Follow-up studies may explore an approach integrating systematic reviews to assess MMER comprehensively. It can also be combined with the content analysis method to evaluate the specific advantages of each document and then summarise.

Declaration of several items of PRISMA2020 were not applicable in our study

1. The authors only followed the steps in scrutiny and do not conduct systematic literature review as per PRISMA methodology. That is why items 2&24&25 was not applicable.
2. The method section of this study describes how we conducted a systematic review with reference to the PRISMA guidelines. The flow chart (see Fig. 1) shows our review steps more intuitively and clearly. The method used is bibliometric analysis, using the CiteSpace quantitative analysis tool. Due to the limitations of the research method, our analysis of the included literature was mainly a macro-evaluation, which did not allow an assessment of the individual value of each article. That is why items 10–15&17-22 were not applicable.

Ethical statement

Review and/or approval by an ethics committee was not needed for this study because no animal or human participants were involved.

Data availability statement

All data associated with this study wasn't deposited into a publicly available repository, because it will be made available on request from the corresponding author.

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CRediT authorship contribution statement

Min Jian: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Dongxue Jin:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Dongxue Jin reports financial support was provided by The Social Science Fund Project of Jilin Province in 2022 (Doctoral and Youth Support Project) Practical Research on Cultivating Interdisciplinary Teaching Literacy of Normal Science Students under the Background of New Curriculum Reform (2022C90). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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