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Bibliometric analysis of cognitive regulation models in science education: Trends, key contributors, and research impact

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ABSTRACT
This study presents a bibliometric analysis of cognitive regulation models in science education, focusing on STEM (Science, Technology, Engineering and Mathematics) contexts between 2004 and 2024. Using the Scopus database and VOSviewer (version 1.6.17) and Bibliometrix (RStudio version 4.4.1), we identified Self-Regulated Learning (SRL) as a key theme, strongly linked to motivation, self-efficacy and academic performance. Emerging areas—such as emotional regulation and digital learning environments—highlight the field's response to challenges such as the COVID-19 pandemic. Key findings emphasise that integrating learning analytics, blended instruction, and formative assessments can enhance SRL outcomes in both traditional and online settings. However, emotional regulation and SRL application in large-scale online platforms remain underexplored. We conclude that personalised feedback and metacognitive strategies are vital for improving learners' self-regulation. Future studies should focus on emotional regulation, technology-driven interventions, and interdisciplinary approaches to foster student success in STEM.

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Introduction

Background and Rationale

Cognitive regulation models play a crucial role in educational research (Azevedo, 2020; Schunk & Zimmerman, 2007; Wirth et al., 2020) due to their significant impact on learning outcomes, especially in science education. These frameworks explain how learners regulate their cognitive, emotional, and metacognitive processes—vital for academic performance and critical thinking. In STEM disciplines such as biology, chemistry and physics, effective cognitive regulation is essential for tackling abstract concepts and developing self-directed learning skills (Suryawati et al., 2024). Therefore, examining these models helps optimise academic outcomes by addressing both cognitive and emotional demands.

Self-Regulated Learning (SRL), rooted in Bandura's social cognitive theory, is a core cognitive regulation model emphasising independent learning through self-assessment, planning, and reflection

(Schunk & Zimmerman, 2007). Learners employing SRL strategies (e.g., goal-setting, self-monitoring, reflection) often demonstrate higher academic success, particularly in science contexts that demand mastery of complex, abstract material (Dağğöl, 2023). Its relevance in science education, through goal-setting and progress evaluation, highlights how SRL guides focused and critical thinking (Fitriani et al., 2024; Fatmawati et al. 2025).

Other models, such as Metacognitive Awareness and Cognitive Emotion Regulation (CER), complement SRL by enhancing learning. Metacognitive Awareness involves the ability to monitor and regulate cognition, improving academic performance through the adjustment of learning strategies (Muhali et al., 2019; Wirzal et al., 2022). Learners with high metacognitive awareness tend to perform better by recognising knowledge gaps and modifying their approaches (Abdelrahman, 2020; Asy'ari et al., 2019; Azevedo, 2020). In science education, fostering metacognitive skills leads to deeper understanding and improved problem-solving (Taşçi & Yurdugül, 2017).

CER emphasises managing emotional responses to learning challenges, which can significantly affect academic performance. Adaptive strategies, such as cognitive reappraisal, reduce anxiety and enhance learning, while maladaptive strategies, like rumination, can exacerbate stress (Sun et al., 2020). Addressing both cognitive and emotional aspects of learning, particularly in science education, helps learners persevere through challenges.

These models collectively illustrate the need for holistic educational approaches. By integrating SRL, Metacognitive Awareness, and CER into instructional strategies, educators can create environments that support both cognitive and emotional regulation, fostering resilience and enhancing problem-solving skills (Wirth et al., 2020).

Bibliometric analysis offers a powerful tool for mapping the evolution of cognitive regulation models in STEM. Such analysis is particularly needed to unify fragmented research and identify emerging trends, key contributors, and interdisciplinary collaborations (Djeki et al., 2022). By examining publication volume, citation networks, and keyword clusters, VOSviewer and Bibliometrix highlight how cognitive regulation studies intersect psychology, education, and neuroscience, thus enriching our holistic understanding of the field.

However, bibliometric studies face limitations in data completeness and representativeness. Exclusive reliance on databases such as Scopus or Web of Science can overlook significant contributions from broader sources such as Google Scholar, and citation counts may not fully reflect the quality or impact of research (Polat, 2022). Therefore, it is important to supplement bibliometric data with qualitative insights for a comprehensive view.

Cognitive regulation models remain vital for enhancing learning outcomes in science education, addressing both cognitive and emotional learning dimensions. By fostering SRL, metacognition, and emotional regulation, these models equip learners to thrive in demanding academic environments. Bibliometric analysis will continue to be a critical tool in guiding future research and understanding the evolving impact of cognitive regulation.

Research Gaps

Despite the growing interest, research on cognitive regulation models in science education remains inconsistently integrated. This fragmentation makes it difficult to compare studies and develop a unified framework for categorising key strategies (Nakhostin-Khayyat et al., 2024; Yusupov et al., 2020). While SRL and metacognitive approaches are well-documented, standardised definitions and operationalisations are lacking, impeding cohesive progress in science education contexts.

A major gap is the absence of consensus on defining and operationalising cognitive regulation models. Researchers vary in their approaches, some emphasising self-regulation's role in enhancing cognitive flexibility, while others highlight the interplay between metacognition and emotional regulation. This variation creates a fragmented research landscape, making comparisons and standardisation difficult, especially in science education (Nakhostin-Khayyat et al., 2024; Yusupov et al., 2020).

Furthermore, many studies fail to address the specific demands of science education. Critical thinking, problem-solving, and managing complex information are often overlooked in favour of general educational contexts. Existing research shows SRL promotes autonomy and motivation (Balashov et al., 2021), but strategies tailored for science disciplines such as biology, chemistry and physics remain underexplored (Eker & İnce, 2018).

Another challenge lies in the lack of methodological consistency. Many studies rely on self-reported data, which can introduce biases and may not accurately reflect learners' cognitive processes (Dang et al., 2020; Fan et al., 2022; Van Der Ham et al., 2021; Villegas & Panoy, 2023). Additionally, diverse assessment tools and frameworks complicate meaningful comparisons and limit evidence-based interventions in science education (Eker & İnce, 2018).

The interaction between cognitive regulation and factors such as motivation, emotional intelligence, and social dynamics remains insufficiently explored. For example, emotional intelligence's role in facilitating cognitive regulation could provide insights into how learners manage stress and the cognitive demands of science learning (Amponsah et al., 2024; Mukhametzyanova, 2021). Moreover, understanding the contributions of key researchers, institutions and countries in cognitive regulation research is needed. Mapping collaboration networks can enhance knowledge-sharing and interdisciplinary research (Muñoz et al., 2016).

The integration of technology into science education presents additional opportunities and challenges. While digital tools and online platforms have transformed engagement with content, gaps remain in leveraging these tools to support SRL, metacognitive awareness, and emotional regulation in remote and hybrid learning environments (Hung & Young, 2021). Research needs to explore how technology can enhance these processes, particularly in large-scale online contexts.

Finally, the evolution of cognitive regulation models across different contexts remains underexplored. Bibliometric analysis, as applied by Wang and Hasim (2024) in technology-enhanced learning, has yet to be fully applied to science education. This approach could identify emerging themes, key contributors, and research gaps, providing a clearer picture of the models' development over time.

Addressing these gaps—unified frameworks, context-specific research, methodological rigor, and interdisciplinary exploration—through advanced methodologies like bibliometric analysis will be crucial for advancing the study of cognitive regulation in science education.

Research Objectives

The primary objective of this bibliometric study was to investigate cognitive regulation models in STEM education, focusing on trends, key contributors, and research impact between 2004 and 2024. More specifically, we aimed to identify publication trends and geographical distribution, examine collaboration networks and top contributors, and elucidate how cognitive regulation research has developed over time. These goals offer insights into emerging themes and pave the way for future research directions.

The research sought to identify key contributors—authors, institutions and countries—that played a pivotal role in advancing the study of cognitive regulation in science education. By examining influential publications and journals, the study highlighted the most impactful research and clarified where academic efforts had been concentrated. We formulated the following research questions to guide our analysis:

1. RQ1: What are the main publication trends and key journals in cognitive regulation for STEM education?
2. RQ2: Who are the top authors, institutions, and countries contributing to this field, and how do they collaborate?
3. RQ3: Which themes and topics have emerged over time, and what gaps or future directions can be identified?

Literature Review

Theoretical Foundation of Cognitive Regulation Models

Cognitive regulation, Self-Regulated Learning (SRL), and metacognitive strategies are central in educational psychology, particularly in science education where learners face complex concepts and must develop autonomy and critical thinking (Prayogi et al., 2025). These interdependent constructs enable learners to plan, monitor, and adjust their study approaches, leading to improved academic success in disciplines such as biology, chemistry and physics. Cognitive regulation involves managing cognitive processes (e.g., planning, monitoring, evaluating learning strategies) to achieve effective outcomes (Nguyen & Ikeda, 2015). In science education, this is vital for tackling abstract concepts in physics, biolofy or chemistry, prompting strategy adaptation through self-assessment. Strong cognitive regulation supports critical thinking, elaboration, and synthesis—skills essential for mastering scientific material. SRL integrates cognitive regulation with motivation and emotion, allowing learners to take control of their education via goal-setting, strategy selection, and reflection (Cassidy, 2011; Lavi et al., 2019). In science courses, SRL is critical for managing both cognitive tasks and emotional demands. Evidence shows SRL strategies (e.g., setting goals, monitoring progress) enhance academic performance, motivation and problem-solving abilities (Radović et al., 2024; Theobald, 2021; Jansen et al., 2019).

Metacognitive strategies, a core element of SRL, encompass awareness and control of one's cognitive processes (Muhali et al., 2019). In science education, where higher-order thinking is frequently required, metacognitive approaches (e.g., self-questioning, reflective thinking) enable learners to evaluate understanding and adjust study techniques (Ulfatun et al., 2021). This is particularly beneficial for grasping complex concepts such as chemical reactions. Combining cognitive regulation, SRL, and metacognition is key for science curricula involving abstract concepts and inquiry-based tasks. Methods like problem-based learning and inquiry-based learning strengthen student engagement, prompting goal-setting and reflection (Jaramillo et al., 2022). Nonetheless, implementing these models can be challenging in online or hybrid settings, where lack of external structures and limited teacher scaffolding may hinder self-regulation (Calamlam et al., 2022). Educators often require professional development to effectively teach these strategies and create environments conducive to SRL (Stephen & Rockinson-Szapkiw, 2021).

Collaborative learning in science also benefits from cognitive regulation, requiring "socially shared regulation," where group members jointly plan and monitor learning (Isohätälä et al., 2017). Such collaboration can boost feedback and peer support, enhancing learning outcomes in science classrooms (Anderson et al., 2023). In summary, cognitive regulation, SRL, and metacognition are critical to effective science learning. They empower learners to self-manage, stay motivated, and master complex content. However, barriers remain in virtual and collaborative settings, making targeted teacher training and instructional interventions vital for maximising the impact of these strategies on outcomes.

Previous Studies Using Bibliometric Analysis

Bibliometric analysis is frequently employed to uncover research trends, key contributors, and emerging themes in education. It has been used in fields such as SRL, mobile-assisted language learning (MALL), and emergency remote teaching (ERT), providing useful comparisons for our focus on cognitive regulation in science (Wang & Hasim, 2024; Tonbuloğlu & Avcı Akbel, 2023). SRL is extensively studied, with bibliometric work (e.g., Sulistiawati et al., 2023) revealing key trends from 1990–2022 across 2,106 documents. This underscores SRL's importance in digital settings and performance outcomes—insights that parallel our examination of cognitive regulation in science. Similarly, Turmuzi et al. (2023) focused on MALL, illustrating how mobile tools support self-regulation. Although language-focused, their findings about technology's role in self-regulation are relevant for science contexts, reinforcing the theme of tech-enhanced cognitive regulation. With emergency remote teaching (ERT), researchers (e.g., Mäkipää et al., 2022; Chan & Daigle, 2022) highlighted the importance of flexible cognitive regulation amid rapid shifts to online learning. These findings inform how external factors (crises, tech changes) influence self-regulation, paralleling science education's need for adaptable strategies in dynamic settings.

Unlike studies on language or COVID-related topics, our work centres on cognitive regulation in science education. This approach reveals how learners handle complex scientific content through self-directed learning and enhanced academic achievement. While SRL and MALL analyses provide foundational insights, our focus on STEM brings fresh perspectives on applying these theories in discipline-specific contexts. Wang and Hasim (2024) also examined self-regulated language learning in mobile contexts, illustrating the role of technology in bolstering self-regulation. Their methods (e.g., co-occurrence and burstness analyses) are transferable to cognitive regulation research in science education. Tonbuloğlu and Avcı Akbel's (2023) analysis of ERT trends exemplifies how global crises influence educational practices and collaborations. Our study parallels their approach by examining publication patterns and networks, but focuses on long-term theoretical shifts in cognitive regulation for science. In conclusion, SRL, MALL, and ERT bibliometric studies underline the value of mapping research trends, contributors, and themes. Our study extends these methodologies, revealing how cognitive regulation models shape science education, thus informing future practices and theoretical progress.

Method

Research Design

This study employed a bibliometric analysis guided by the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to examine trends, contributors, and research impact in cognitive regulation for science education. Bibliometric analysis quantitatively maps scientific literature, revealing trends, key publications, co-occurring keywords, and citation networks (Farooq et al., 2024; Prahani et al., 2022). Our goal was to offer a comprehensive overview of existing literature on cognitive regulation (focusing on SRL and metacognitive strategies) and their use in STEM contexts.

Data Source and Search Strategy

The literature originated from Scopus, selected for its broad coverage of peer-reviewed journals. We used ("cognitive regulation" OR "self-regulated learning" OR "metacognitive strategies") AND ("science education" OR "STEM education" OR "higher education" OR "university") as our query, conducted in June 2024. A 20-year range (2004–2024) was chosen to capture two decades of evolving research in a maturing field. We limited the results to English articles to maintain consistency and focus on widely cited, high-impact publications.

PRISMA Protocol

A systematic PRISMA-based approach helped us identify, screen, and include relevant documents. Table 1 outlines the stepwise method, ensuring transparency and reproducibility in our selection process.

Table 1

PRISMA protocol utilised.

Step	Details
Database	Scopus
Time span	2004-2024
Document type	Peer-reviewed articles
Language	English
Identification	2,511 articles identified through the search query
Screening	789 irrelevant publications removed; 60 review articles excluded
Final inclusion	1,662 articles included in the final analysis

During the screening phase, publications were excluded based on relevance, resulting in a dataset of 1,662 original research articles focused on cognitive regulation in science education or STEM fields.

Data Analysis

The analysis comprised three components. First, a keyword co-occurrence analysis used VOSviewer (version 1.6.17) to visualise relationships among key topics. Frequent terms—such as self-regulated learning, motivation, and self-efficacy—emerged as dominant, while emotion regulation and blended learning were less explored but showcased emerging interests.

Second, a citation network analysis was performed via Bibliometrix in RStudio (version 4.4.1), mapping relationships and calculating metrics (e.g., centrality, impact). Prominent clusters revolved around self-regulated learning and learning analytics, while a cluster on academic procrastination also exhibited noteworthy influence in higher education.

Lastly, thematic evolution analysis examined research shifts in five periods (2004–2014, 2015–2017, 2018–2019, 2020–2021, 2022–2024). Earlier studies emphasised e-learning and academic performance, while recent works highlighted metacognitive strategies and COVID-19 impacts, indicating growing attention to emotional and social dimensions of self-regulation.

Tools and Software

We utilised VOSviewer (version 1.6.17) to create keyword co-occurrence maps and Bibliometrix in RStudio (version 4.4.1) for citation and thematic analysis, leveraging their robust capabilities to uncover trends and collaborations in the dataset.

Validity and Reliability

The Scopus database provided a high-quality, peer-reviewed source pool (Fatawi et al., 2024). VOSviewer and Bibliometrix are established, validated bibliometric tools, ensuring reliable outcomes. Multiple researchers verified the analyses to maintain consistency. To further enhance reliability, two independent researchers applied our inclusion/exclusion criteria to a randomly selected subset of 200 articles from the total dataset. Each researcher independently coded articles for inclusion or exclusion. Afterward, we compared their decisions using Cohen’s kappa (K) to measure inter-rater agreement beyond chance (Landis & Koch, 1977). Our analysis yielded a K value of 0.85, indicating strong inter-rater reliability. Discrepancies on the remaining articles were resolved through discussion, ensuring all final decisions aligned with the study’s scope and quality standards.

Ethical Considerations

As this study used secondary data from the Scopus database, all information was publicly available and ethically sourced. No human subjects or sensitive data were involved, so ethical approval was not required.

Method Limitations

A key limitation is our exclusive use of Scopus, potentially excluding relevant works from other databases. Moreover, bibliometric methods highlight quantitative patterns, possibly overlooking depth in individual studies. Future work could incorporate qualitative content analysis for a broader view of cognitive regulation in science education.

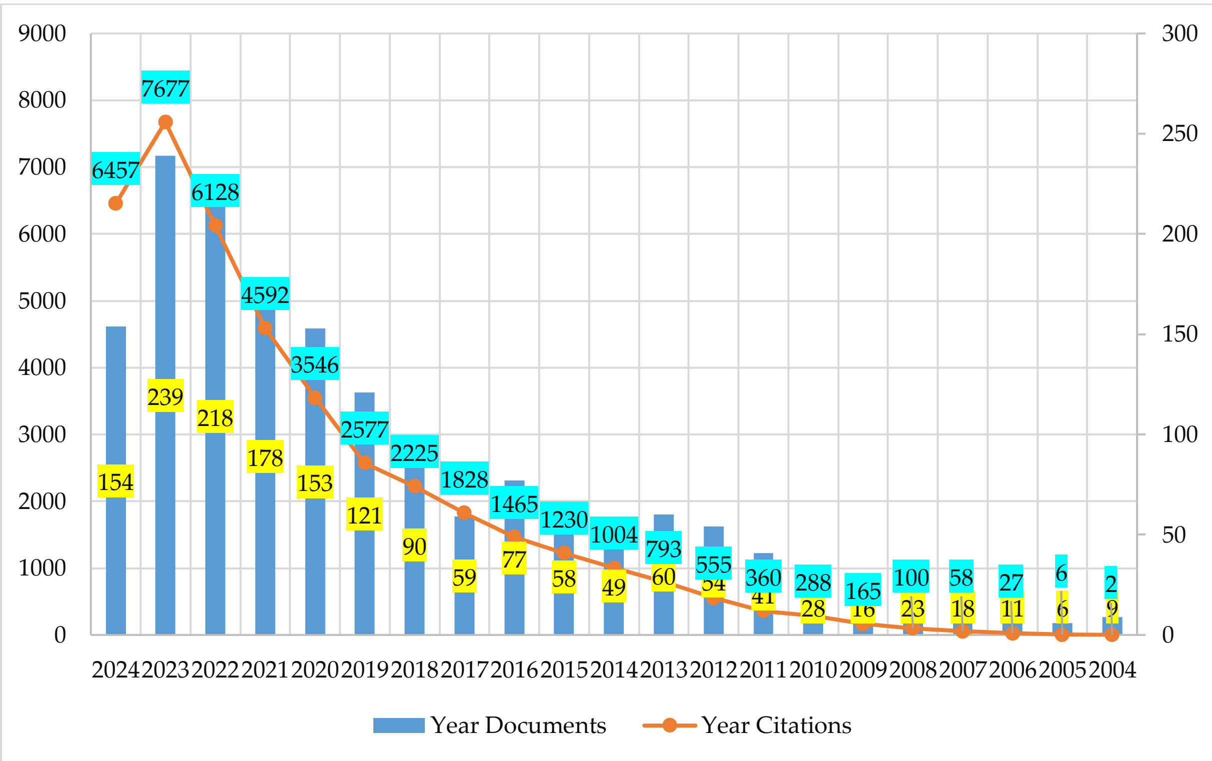
Results

Publication Trends in Cognitive Regulation Models

Research on cognitive regulation in science education has grown markedly over the past two decades. Figure 1 displays annual publication and citation counts (2004–2024), showing increased academic interest. While publication volume has risen, citation data indicate a gradual impact uptake, suggesting the field is still maturing in terms of scholarly influence.

Figure 1

Publication trends of cognitive regulation models in science education



From 2020 onward, publications rose sharply (e.g., 239 in 2023 vs. 9 in 2004). This jump aligns with a wider trend in education, emphasising cognitive processes (e.g., metacognition, emotional regulation) and their impact on learning. Although publication numbers soared, citation growth lagged (peaking at ~7,677 in 2023). Early years (e.g., only 2 citations in 2004) illustrate how recognition of new studies takes time, exhibiting a delayed academic impact. The lag reflects the field's novelty, competition from a large volume of publications, and its interdisciplinary nature, which can dilute immediate visibility within specific domains. A key emerging theme is Self-Regulated Learning (SRL), crucial for independent inquiry and problem-solving in science. Research (Lin et al., 2019) observed an SRL surge (2013–2017), reflecting its foundational role in cognitive regulation. Embodied cognition has also grown in relevance, tying learning to physical experiences. In science education, hands-on methods (Kersting et al., 2021) are used to reinforce cognitive regulation, enabling deeper conceptual understanding. Technology (VR, AI, intelligent systems) has further propelled research on cognitive regulation. Tools like VR (Li et al., 2024) offer real-time feedback, aiding visualisation of abstract concepts and supporting enhanced regulation. Collaborative learning and socially shared regulation are gaining prominence, with group settings fostering mutual monitoring and strategy adjustment. Such social interactions bolster problem-solving and highlight the collective aspect of cognitive regulation. Despite expansion, citation growth remains gradual. As recent studies mature, their impact may increase. Interdisciplinarity also disperses citations across fields, slowing accumulation in a single domain. In summary, publication trends show a rapidly growing field, underscoring the importance of SRL, metacognition, and emotional regulation in science education. Citation impact, however, lags, likely due to field novelty and interdisciplinary breadth. Nonetheless, as research matures, impact should strengthen, deepening our understanding of cognitive regulation in STEM.

Key Contributors

Research on cognitive regulation in science education has been driven by several prolific scholars and institutions over the last two decades. Tables 2 and 3, plus Figure 2, highlight leading contributors and collaborations in the field. Table 2 shows the top 10 authors, based on number of articles and AF (Article Fractionalized-indicate each author's individual contribution to their publications) scores. Lawrence Jun Zhang (AF 4.75) stands out for significant work (based on N of documents) on metacognitive strategies and SRL.

Table 2

Top 10 most prolific authors

Authors	Articles	AF	Affiliation	Country
Gašević, Dragan	11	1.81	Monash University	Australia
Panadero, Ernesto	11	2.90	Dublin City University	Ireland
Zhang, Lawrence Jun	11	4.75	The University of Auckland	New Zealand
De La Fuente, Jesús	10	2.33	University of Navarra Pamplona	Spain
Bellhäuser, Henrik	9	2.68	Johannes Gutenberg-Universität Mainz	Germany
Bernacki, Matthew L.	9	2.45	The University of North Carolina	United States
Dresel, Markus	9	1.93	Universität Augsburg	Germany
Tsai, Chin-Chung	9	2.67	National Taiwan Normal University	Taiwan
Broadbent, Jaclyn	8	3.67	Deakin University	Australia
Tsai, Chia-Wen	8	6.17	Ming Chuan University	Taiwan

Chia-Wen Tsai has the highest AF (6.17), reflecting strong individual contributions in tech-enhanced contexts, while Jaclyn Broadbent (AF 3.67) focuses on blended and online learning. Ernesto Panadero (AF 2.90), despite 11 publications, has collaborative work on SRL and formative assessment, showing diverse influence. Table 3 and Table 4 shows top affiliations and countries in cognitive regulation research. The University of Granada (40 articles) and Maastricht University (38) highlight Europe's prominence, while the USA (657) and China (485) lead globally, reflecting the field's international nature.

Figure 2 (co-authorship network) illustrates collaboration clusters among key researchers, each node sized by number of co-authored papers. Lines indicate collaboration strength, revealing regional or institution-based partnerships.

One cluster features Bellhäuser, Dresel, and Schmitz (Germany), focusing on motivation and cognitive regulation. Gašević collaborates with van der Graaf and Fan Yijun on learning analytics and SRL, demonstrating the role of technology in cognitive regulation. Another group is led by Zhang, focusing on metacognitive strategies in higher education, while Panadero's cluster highlights SRL and assessment practices across European contexts. Overall, the co-authorship network reveals both close collaborations and isolated research hubs, with regional ties (notably in Europe) facilitating partnerships and interdisciplinary efforts.

Table 3

Top 10 most prolific affiliations

Affiliation	Articles
University of Granada	40
Maastricht University	38
Islamic Azad University	31
McGill University	30
University of North Carolina	30
University of Vienna	29
Utrecht University	28
Newcastle University	25
The Education University of Hong Kong	25
University of Macau	25

Table 4

Top 10 most prolific countries

Country	Articles
USA	657
China	485
Spain	417
Germany	344
UK	300
Netherlands	258
Australia	257
Indonesia	233
Malaysia	175
Iran	160

Interdisciplinary collaboration (e.g., psychology, neuroscience, ed tech) and strong institutional support (e.g., Monash, Auckland) enrich research depth and citation impact, as seen with Gašević and Zhang. Active networking (e.g., conferences, professional groups) boosts collaboration and visibility, fueling influential work and methodological innovation. Despite advances, a lack of longitudinal studies persists, limiting understanding of how cognitive regulation evolves over time. Future work should include extended tracking of these strategies' long-term impact. Additionally, a higher education focus restricts generalisability. Including K–12 and informal contexts would broaden the applicability of cognitive regulation models. In summary, leading figures like Gašević, Panadero, and Zhang significantly shape cognitive regulation research, especially in tech-enhanced and science-focused environments. Collaborative networks span the globe, with USA, China and Spain leading in publication counts. Such partnerships will continue driving innovation and broadening the impact of cognitive regulation in diverse educational contexts.

Figure 2

Co-authorship network

Influential Publications and Journals

Over the past two decades, cognitive regulation in science education has seen substantial growth, with key journals and publications shaping its evolution. Identifying influential outlets and articles reveals major research trends, top contributors, and emerging directions. Such analysis helps researchers pinpoint advancements and anticipate future needs in cognitive regulation scholarship. The leading journals demonstrate the field's interdisciplinary scope. Table 5 shows Computers and Education having the highest h-index (20) and g-index (23). Since 2008, it has published 23 highly cited papers (1,865 citations), focusing on technological tools for SRL and metacognition—a key trend in educational research. Frontiers in Psychology has emerged quickly, holding the highest g-index (29) and most publications (64). Its psychological orientation—especially on emotional regulation and motivation—positions it as a crucial source for understanding how cognitive and affective factors intersect in learning.

Table 5

Top 10 most influential journals

Source	h_index	g_index	m_index	*TC	*NP	*PY_start
Computers and Education	20	23	1.176	1865	23	2008
Learning and Individual Differences	18	19	1.059	901	19	2008
Frontiers in Psychology	17	29	1.7	1027	64	2015
Computers in Human Behavior	16	16	0.889	1716	16	2007
Internet and Higher Education	16	18	1	3241	18	2009
Studies in Higher Education	14	16	1	1082	16	2011
Education and Information Technologies	12	21	1.333	647	21	2016
Metacognition and Learning	12	17	0.8	584	17	2010
Sustainability (Switzerland)	11	19	2.2	395	29	2020
System	11	23	0.579	683	23	2006

Note. *TC: Total Citations; *NP: Number of Publication; *PY: Publication Year

A notable journal, The Internet and Higher Education, with 3,241 citations (18 publications since 2009), examines how digital environments shape cognitive regulation. As online learning grows, this resource offers relevant perspectives on virtual classroom demands. Among newer outlets, Sustainability (Switzerland) shows notable impact (m-index 2.2) since 2020, with 395 citations. Its focus on sustainability in education underscores the rising theme of merging environmental and educational concerns, including sustainable learning's role in cognitive regulation. Influence also derives from landmark articles. Table 6 shows Pekrun et al. (2011) as top-cited (1,373 total; 98.07/year). Their Achievement Emotions Questionnaire (AEQ) study illuminates how emotions (e.g., anxiety, joy) shape learning, influencing instructional design and pedagogy.

Table 6

Top 10 most influential articles

Authors	Title	*TC	*TCY	*NTC
(Pekrun et al., 2011)	Measuring emotions in learners' learning and performance: The Achievement Emotions Questionnaire (AEQ)	1373	98.07	13.85
(Dabbagh & Kitsantas, 2012)	Personal Learning Environments, social media, and self-regulated learning: A natural formula for connecting formal and informal learning	1065	81.92	19.60
(Schraw et al., 2006)	Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning	786	41.37	5.25
(Blair & Diamond, 2008)	Biological processes in prevention and intervention: The promotion of self-regulation as a means of preventing school failure	756	44.47	8.01
(Rosen et al., 2013)	Facebook and texting made me do it: Media-induced task-switching while studying	511	42.58	16.11
(Carless et al., 2011)	Developing sustainable feedback practices	508	36.29	5.13
(Broadbent, 2017)	Comparing online and blended learner's self-regulated learning strategies and academic performance	438	54.75	10.97
(Littlejohn et al., 2016)	Learning in MOOCs: Motivations and self-regulated learning in MOOCs	421	46.78	11.10
(Tai et al., 2018)	Developing evaluative judgement: enabling learners to make decisions about the quality of work	406	58.00	14.53
(Hadwin & Oshige, 2011)	Self-regulation, coregulation, and socially shared regulation: Exploring perspectives of social in self-regulated learning theory	371	26.50	3.74

Note *TC: Total Citations; *TCY: TC per Year; *NTC: Normalized TC

Blair and Diamond (2008) examined biological underpinnings of self-regulation to prevent school failure. With 756 citations, they broadened the field to developmental and neurological aspects, underscoring how biology affects long-term learning regulation. Rosen et al. (2013) address media multitasking (511 citations) and its cognitive toll, linking digital distractions to reduced engagement in learning. With technology's growing role, media usage and its effects on cognitive regulation remain crucial research areas. Carless et al. (2011) (508 citations) highlight sustainable feedback practices that foster SRL. Their work emphasizes actionable, reflective feedback, aligning with formative assessment trends and learner autonomy.

Overall, these journals and publications underscore major themes: emotional regulation, technology integration, media influence, and feedback. Metrics (h-index, g-index, m-index) clarify their impact, while interdisciplinary work is key for broadening the field. As research advances, emotional regulation, digital tools, and effective feedback will stay central, guided by collaborative efforts and innovative technologies.

Keyword Co-Occurrence and Emerging Themes

A keyword co-occurrence analysis uncovers major themes in cognitive regulation research within science education. Figure 3 depicts frequent keywords and their interrelationships, grouped into clusters like self-regulated learning, cognitive strategies, digital literacy, and feedback. These clusters illustrate the field's varied focal points and indicate emerging directions in both traditional and technology-driven learning.

The green cluster centres on Self-Regulated Learning (SRL) and Performance. Self-regulated learning dominates, indicating its pivotal place in cognitive regulation. Keywords such as motivation, self-efficacy, and academic achievement underscore how SRL drives better outcomes (Broadbent, 2017; Uçar, 2018). Intrinsic motivation also matters, as emotions (anxiety, joy) deeply shape learning (Pekrun et al., 2011).

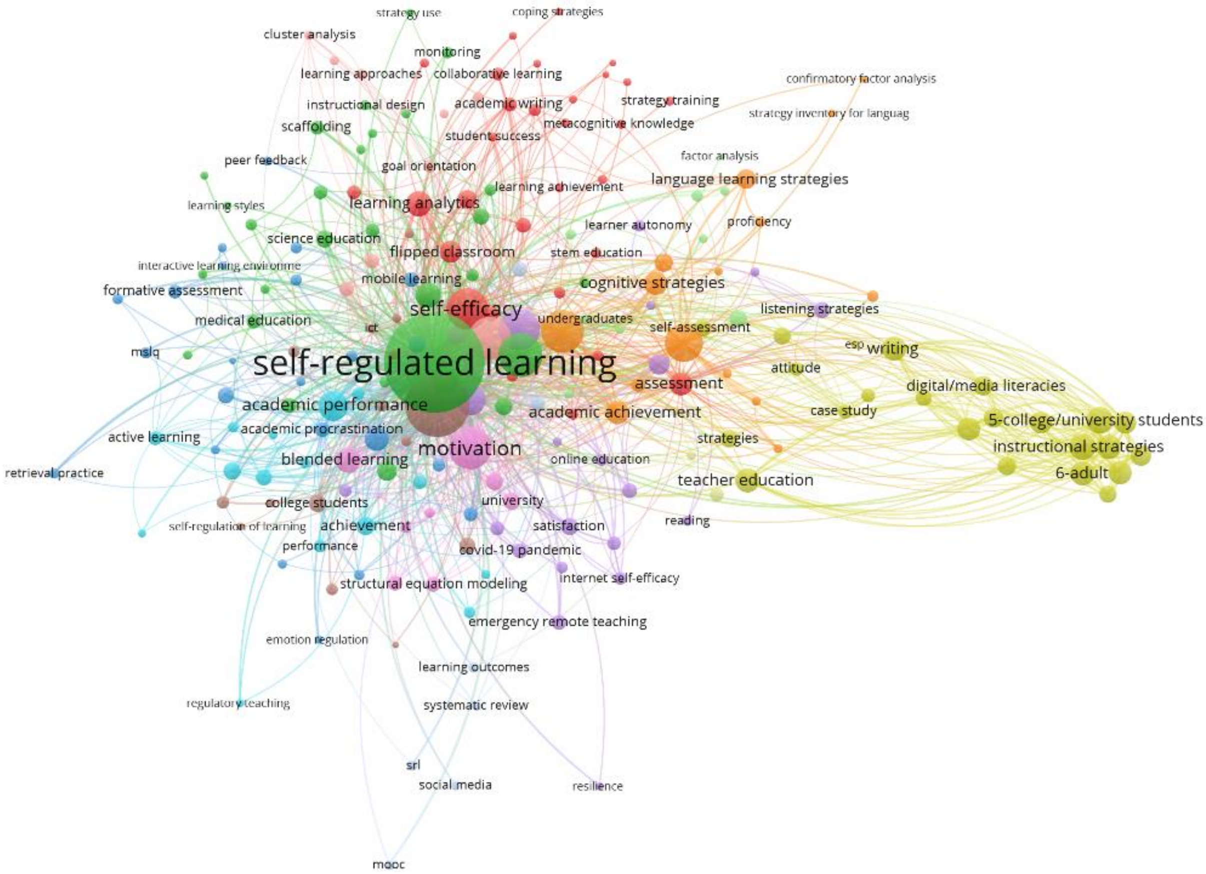
The red cluster highlights Cognitive and Learning Strategies, including learner autonomy and language strategies. Studies (Leopold & Leutner, 2015; Hattie & Donoghue, 2016) confirm that organisational tools, rehearsal, and elaboration boost comprehension and complex concept mastery. Educators' roles in teaching these strategies are essential, as collaborative learning and teacher training help foster autonomy (Arthur & Akwetey, 2021; Schraw et al., 2006).

The blue cluster focuses on Active Learning and Feedback, featuring keywords like peer feedback and flipped classroom. Carless et al. (2011) show how ongoing feedback enhances reflection and adjustment. With learning analytics and formative assessment (Tai et al., 2018), data-driven support for self-regulation is increasing. Peer feedback also promotes self-regulation by developing evaluative skills (Er et al., 2021).

The yellow cluster underscores Digital Literacy and Instructional Strategies. Digital literacies (Khlaisang & Yoshida, 2022) empower learners to find, evaluate, and apply resources for better self-regulation. Tools like online platforms and interactive multimedia (Rini et al., 2022) facilitate goal-setting, tracking, and strategy adjustments. Consequently, instructional methods focusing on digital skill development are increasingly common to foster SRL and academic performance.

Figure 3

Research trends based on keyword co-occurrence



The purple cluster addresses Learning Outcomes and Remote Teaching, showing how COVID-19 reshaped self-regulation demands. Remote settings require higher autonomy, with keywords like emotion regulation, self-efficacy, and digital literacy (Sukirman et al., 2022). Time management, motivation and feedback become critical (Alqahtani & Rajkhan, 2020). Emotional strain (Mahyoob, 2020) can compound self-regulation challenges, although supportive digital platforms (Liu et al., 2022) can alleviate isolation and boost collaboration.

Lastly, the orange cluster highlights Language Learning and Strategies, where self-regulation theories support goal-setting and monitoring (Dabbagh & Kitsantas, 2012). L2 learners rely on autonomy beyond formal instruction, prompting instructional designs that embed SRL for grammar, vocabulary and communication skills (Schraw et al., 2006).

Overall, the co-occurrence map underscores emerging themes: SRL, cognitive/metacognitive strategies, digital literacy, active learning, and COVID-19 impacts. Collectively, they signal the field's emphasis on strengthening student agency in both classroom and online settings. As digital technologies grow, these themes will further influence future research and educational practice.

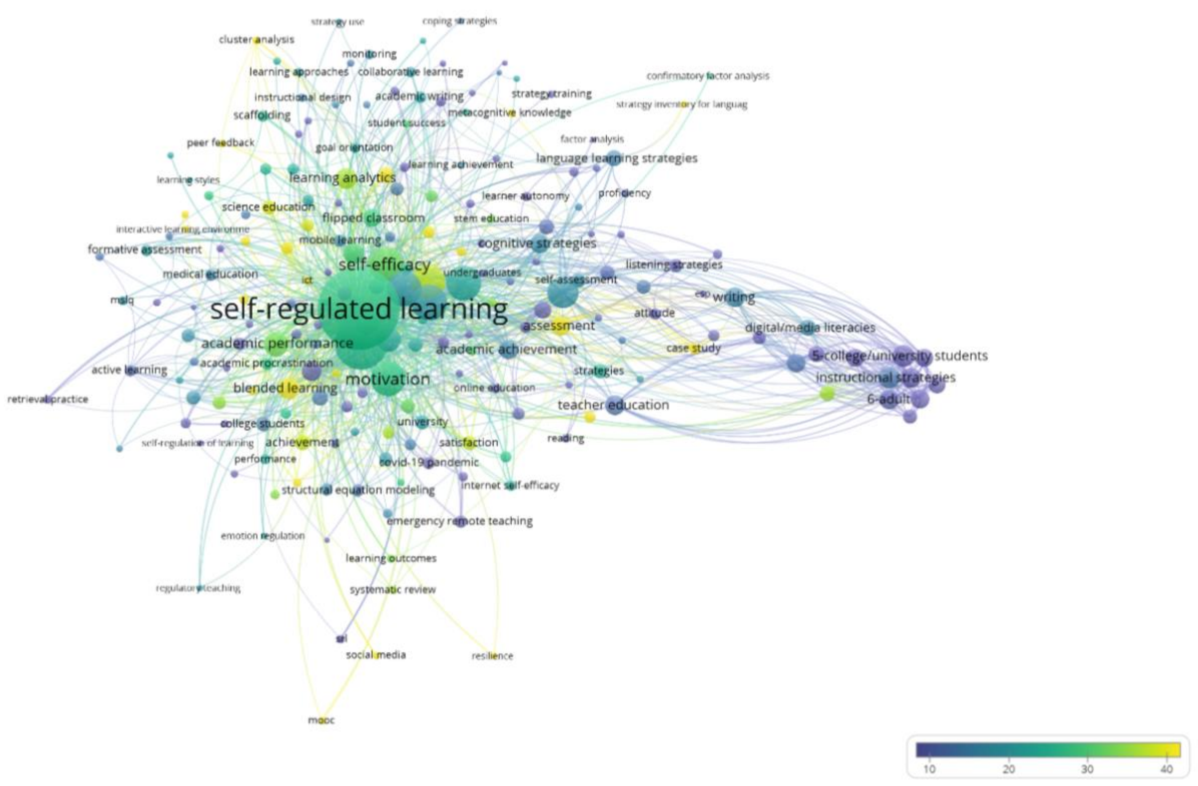
Citation Networks

In bibliometric analysis, citation networks help uncover a field's intellectual structure, connectivity, and impact. Figure 4 depicts keywords in cognitive regulation for science education, sized by occurrence and color-coded by citation count. Green nodes signal frequently cited themes (e.g., SRL, motivation), while blue nodes show newer but growing research areas. Such networks reveal key study directions, foundational works, and emerging subfields.

At the network's centre, green nodes reflect the importance of Self-Regulated Learning (SRL) and motivation, indicating their foundational role. Terms such as self-efficacy, academic performance, and blended learning further demonstrate focus on how self-regulatory strategies shape academic results. For instance, Pekrun et al. (2011) showed how emotions affect SRL, establishing links between motivation, emotion, and performance. Within this green cluster, key terms like goal orientation, scaffolding, and learning analytics illustrate the instructional focus on supporting SRL. Scaffolding research examines phased withdrawal of external supports, while learning analytics provides real-time data to inform self-regulation interventions.

Figure 4

Average citations



Next, the yellow cluster centres on Cognitive and Learning Strategies—keywords such as collaborative learning, monitoring, and rehearsal show how cognitive regulation is used in practical settings (Broadbent, 2017). This cluster also features learner autonomy and assessment, pointing to the application of self-regulation in contexts such as language acquisition, where learners self-manage and evaluate progress.

The blue cluster highlights digital/media literacies and instructional strategies—emerging focus areas. With online platforms becoming mainstream, media literacy has proven vital for self-regulation (Muthupoltotage & Gardner, 2018). High digital literacy enables learners to set goals, monitor progress, and collaborate effectively (Khlaisang & Yoshida, 2022). Moreover, the blue cluster underscores instructional strategies in digital settings, where media literacy merges with design methods. Such research gained traction during COVID-19, when online learning demanded self-directed approaches and flexible pedagogies.

The purple cluster reflects pandemic-driven themes such as remote learning and emotion regulation, highlighting the global shift to online education. Alqahtani and Rajkhan (2020) underscore the criticality of emotion regulation when traditional supports are absent, while Mahyoob (2020) details the psychological challenges (anxiety, isolation) amplified in remote contexts.

Keywords such as emergency remote teaching and self-efficacy also appear here, underlining the concerns about learner self-regulation amid pandemic disruptions. Liu et al. (2022) demonstrate how blended environments, fostering collaboration and peer feedback, can bolster SRL even under crisis conditions. Emerging terms on the network's edges—MOOCs, social media, resilience—point to new applications of cognitive regulation. MOOCs often demand self-management without strong instructor presence (Broadbent, 2017), and resilience is becoming crucial given global disruptions. As education adapts, research on maintaining motivation and SRL in these contexts is expected to increase.

In summary, the citation network spotlights both core themes (SRL, motivation, self-efficacy) and emerging areas (digital literacy, pandemic-driven remote learning, resilience). Clusters highlight the adaptability of cognitive regulation to various contexts—language learning, online tools, emergency teaching. Future studies will likely expand on digital integration, social media, and informal learning, underscoring the field's dynamic evolution.

Theme Centrality and Evaluation

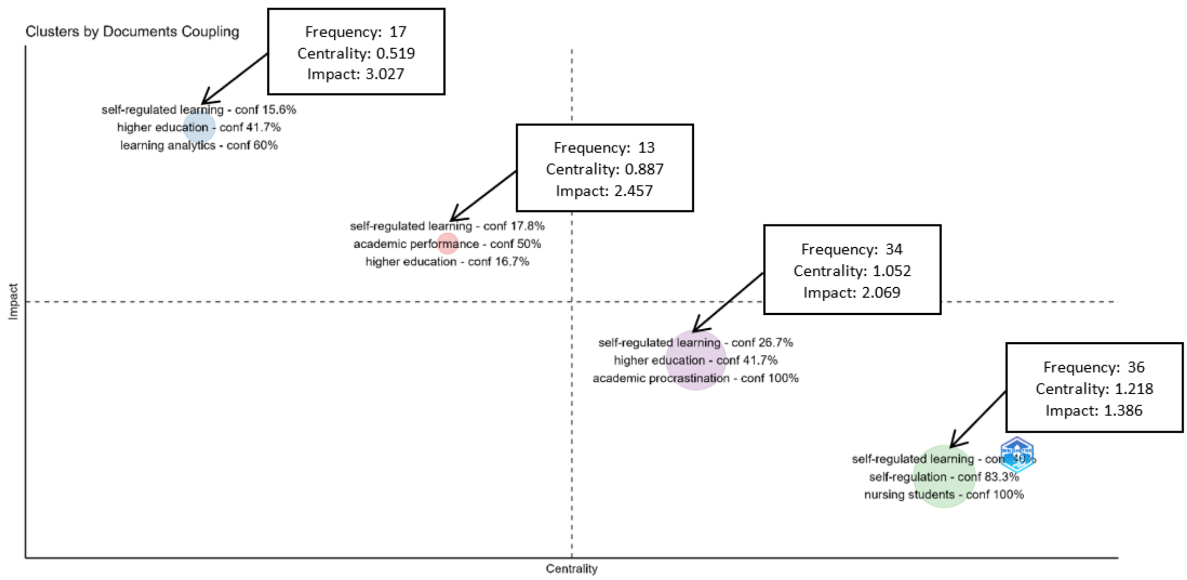
The theme centrality and evolution (Figures 5 & 6) offer key insights into the development of cognitive regulation in science education over time. Figure 5 (document coupling) reveals cluster centrality and impact, while Figure 6 (Sankey) shows how themes evolve (2004–2024), highlighting shifts in focus and breadth.

In Figure 5, centrality (connectivity) and impact (citation strength) determine each cluster's role in the broader landscape. Clusters span niche, high-impact topics to broadly integrated yet less influential areas, reflecting diverse self-regulation focuses in education.

The top-left cluster features SRL, higher education, and learning analytics. Though centrality is low (0.519), impact is high (3.027), indicating influential yet niche work. Focus on learning analytics reveals a cutting-edge, data-driven approach to monitoring and enhancing SRL, especially in online or hybrid environments where behavior tracking fosters self-regulation.

Figure 5

The centrality and impact of key publications



In contrast, the top-right cluster focuses on SRL and academic procrastination, showing high centrality (1.052) and impact (2.069). Procrastination in higher education (100% overlap) signals a major concern, as it undermines self-regulation. High connectivity and strong influence highlight the need to tackle procrastination to boost academic performance and SRL.

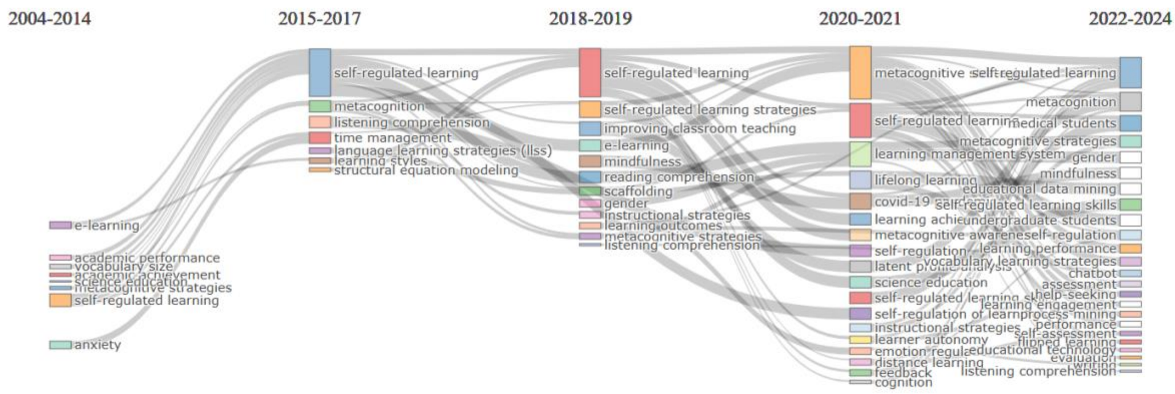
The bottom-right cluster addresses SRL in nursing education, boasting the highest centrality (1.218). Although its impact (1.386) is modest, the high connectivity bridges multiple subfields, pointing to self-regulation in professional contexts. Nursing demands autonomy and self-regulatory competencies, drawing increased focus to professional education settings (Hecke et al., 2024; Assolari et al., 2024), compared to non-STEM disciplines, which may emphasize interpersonal dynamics more prominently (Coluccio et al., 2024; Fei et al., 2024).

The middle cluster, with moderate centrality (0.887) yet high impact (2.457), merges SRL, academic performance, and higher education. This balance of connectivity and influence underscores the importance of understanding how SRL drives academic success. A 50% overlap with higher education reaffirms the practical link between self-regulation and learner performance, guiding interventions to enhance outcomes.

Figure 6 provides a longitudinal perspective (2004–2014, etc.), showing early focus on e-learning, academic performance, and SRL. This established how self-regulation functions in digital environments. Topics such as vocabulary size and anxiety also reveal interest in language acquisition and emotional aspects, reflecting motivation challenges in e-learning.

Figure 6

Theme evolutions in cognitive regulation in science education



From 2015 to 2017, themes such as metacognition, time management, and learning styles gained prominence, signaling a deeper interest in how learners manage cognition for better outcomes. Ongoing emphasis on SRL, combined with listening comprehension and structural equation modeling, demonstrates more granular examinations of how they monitor, evaluate, and adapt learning strategies. During 2018–2019, research broadened again, integrating instructional strategies and emotional factors, such as mindfulness, gender, and scaffolding. This shift underscores the growing importance of social and emotional aspects in self-regulation, with mindfulness emerging as a notable avenue for supporting cognitive regulation in high-autonomy, self-directed settings.

In 2020–2021, a significant expansion occurred, influenced by COVID-19. Themes such as lifelong learning, data mining, and pandemic-related education point to how self-regulation helps learners tackle remote and emergency teaching. The rise of data mining and learning analytics reflects the growing reliance on technology to study and support SRL in online contexts, while lifelong learning emphasises the broader, continuing value of SRL. By 2022–2024, attention turned to metacognitive strategies in specialised fields such as medical education, with renewed interest in gender issues and data mining/feedback. This reveals the continued fusion of social and technological aspects of SRL. The spotlight on medical learners emphasises self-regulation in professional training, demanding high autonomy and cognitive regulation.

Overall, foundational SRL remains central, but the field has broadened to embrace emotional, social and technological factors. The ongoing interest in academic performance, metacognition, and instructional strategies points to a commitment to refining interventions. Meanwhile, data-driven methods and professional education settings highlight an evolving emphasis on meeting 21st-century learner demands in increasingly digital contexts.

Discussion

The findings of this bibliometric analysis reveal that SRL, motivation and self-efficacy form the most frequently studied cluster, with a marked emphasis on academic performance across STEM contexts. Notably, we identified five main research themes—SRL, metacognition, emotional regulation, blended/online learning, and feedback/assessment—which align with existing literature but also underscore where science education research diverges from other fields. This comparative lens highlights the unique focus in science education on practical, inquiry-based activities that demand self-regulatory competencies, whereas other fields may concentrate more on skills development and linguistic proficiency.

Our co-occurrence analysis further revealed that Self-Regulated Learning (SRL) remained central across diverse fields, mirroring findings in language and online education (Broadbent, 2017; Pitenoee et al., 2017). However, the emphasis on motivation and performance in science suggests that interventions such as blended learning and scaffolding are pivotal for supporting inquiry-based tasks. This focus diverges from language education's primary attention on metacognitive awareness for proficiency gains. Hence, a practical outcome of our analysis is that science educators may adapt successful SRL interventions used in language learning—particularly those that strengthen goal-setting and monitoring—to bolster student mastery of complex STEM concepts.

Our findings also underscore a difference in how technology is leveraged: while online education research often places digital platforms (e.g., learning analytics) at the forefront (Khlaisang & Yoshida, 2022), science education tends to view technology as a complementary tool rather than the primary driver of SRL. Specifically, our citation network analysis shows that technology in science education predominantly aims to improve academic achievement via blended instruction and data-driven feedback, reflecting an outcome-oriented approach. This aligns with prior studies highlighting that, in STEM settings, technology is frequently integrated to enhance hands-on or inquiry-based learning rather than to replace it.

From a theoretical standpoint, the prevalence of SRL, motivation, and self-efficacy in STEM research (Uçar, 2018) confirms the strong link between self-regulatory processes and achievement. As indicated by our analysis of the most-cited publications, real-time data from learning analytics (Muthupoltotage & Gardner, 2018) is gradually becoming integral to science curricula, allowing instructors and learners to identify misconceptions and adjust study habits promptly. This finding aligns with broader SRL frameworks, suggesting that the timely availability of performance data is particularly beneficial in abstract STEM domains that demand iterative practice and problem-solving.

Although emotional regulation emerged as an emerging cluster in our keyword co-occurrence map, it received fewer citations and appeared in fewer documents compared to SRL and motivation. This gap is critical, as emotional regulation strongly influences learning persistence and stress management (Menggo et al., 2022). Our results suggest that science education researchers could benefit from integrating emotional regulation strategies (e.g., mindfulness, reflective journaling) into SRL-focused interventions, thereby fostering a more holistic approach that addresses both cognitive and affective dimensions of learning.

Moreover, our findings reveal that large-scale online platforms (e.g., MOOCs) and social media remain under-represented within cognitive regulation research. Consistent with Rini et al. (2022), this highlights a critical need to investigate how structured feedback mechanisms, peer interactions, and digital badges or gamification might bolster SRL within MOOCs. Similarly, examining social media platforms as informal learning spaces could provide insights into how everyday digital practices influence learners' self-regulation, motivation, and collaboration—an area ripe for exploration given the ubiquitous nature of social networking among learners.

Our thematic evolution analysis shows a clear uptick in pandemic-related studies post-2020, demonstrating an urgent demand for research on how learners adapted their SRL strategies amid emergency remote teaching (Ma'rufa & Mustofa, 2021). While immediate solutions often involved makeshift digital tools, few studies have examined long-term adaptability and institutional support structures needed to sustain effective SRL in ongoing hybrid or remote environments. Future investigations should thus consider longitudinal designs to capture how learners evolve and refine their SRL capacities over successive semesters of disrupted learning.

In summary, although our bibliometric analysis reveals robust emphasis on SRL, motivation, and self-efficacy, it also pinpoints critical gaps in emotional regulation, digital platform usage (e.g., MOOCs, social media), and crisis-driven adaptations (e.g., pandemic response). Bridging these gaps will likely require interdisciplinary efforts, integrating psychological frameworks of emotion with educational technology innovations. Such comprehensive approaches could enhance the efficacy of self-regulatory strategies, especially in complex STEM contexts where learning demands are both cognitively and emotionally challenging.

Conclusion and Implications

Our bibliometric findings reveal that SRL, motivation and self-efficacy collectively define the cornerstone of cognitive regulation research in STEM (2004–2024). While emotional regulation, mindfulness, and digital learning show promising growth, they remain comparatively underexplored. By analysing co-occurrence clusters and thematic evolution, we conclude that science education has responded to modern challenges—particularly COVID-19—by increasingly integrating technology and acknowledging learners' emotional needs, although more empirical work is needed to operationalize these insights effectively.

Our evidence supports a trajectory where technology (learning analytics, blended learning, and formative assessment) increasingly underpins SRL-driven instruction. Nevertheless, the relative scarcity of emotional regulation research suggests a need for interventions that address stress, anxiety, and resilience—factors critical to sustaining deep engagement in STEM fields. Hence, we recommend that educators and researchers develop and evaluate emotional-regulation-inclusive strategies to complement the strong focus on cognitive skill-building.

Future research should systematically integrate emotional regulation constructs—such as mindfulness or resilience training—into SRL frameworks for STEM education, particularly in high-stress domains such as the biomedical or nursing fields. Additionally, exploring innovative feedback models (e.g., peer review, automated analytics) in MOOCs or social media-based learning communities can clarify how learners develop and sustain SRL beyond the traditional classroom. Interdisciplinary collaborations (e.g., involving psychologists, technologists, domain specialists) are essential to build robust, evidence-based interventions that produce resilient, self-directed learners in complex STEM environments.

Limitations

First, although our dataset provides a broad overview, the focus on Scopus-indexed articles may omit relevant studies from other databases or in non-English languages. Second, emotional factors (e.g., stress, anxiety) and digital SRL remain less developed, limiting the generalizability of current findings to large-scale or informal online contexts. Finally, the reliance on cross-sectional bibliometric methods restricts our ability to determine the long-term effectiveness of SRL interventions in dynamic educational settings.

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Declaration of Interest

All authors declared no conflict of interest.

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