

Research Trends of Self-Directed Learning in STEM Education Over The Last Two Decades: A Bibliometric Analysis

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ABSTRACT Self-Directed Learning (SDL) has gained prominence as a core competency in 21st-century education, particularly within STEM domains, where autonomy and digital fluency are increasingly emphasized. However, the evolution and intellectual structure of SDL in STEM education remain underexplored from a bibliometric perspective. This study aims to map research trends, thematic clusters, and major contributors in SDL-STEM literature published between 2005 and 2024. A total of 40 Scopus-indexed articles were analyzed using the Bibliometrix R package and VOSviewer. The analysis included performance indicators, international co-authorship networks, and keyword co-occurrence to identify thematic patterns and knowledge structures. The results show a steady increase in publication output, with an annual growth rate of 9.35%. The United States and Australia lead in publication volume, while Germany and the Netherlands demonstrate strong collaborative engagement. Four thematic clusters were identified: (1) digital pedagogy and instructional practices in STEM, (2) technology-enhanced self-directed learning environments, (3) curriculum design, motivation, and teacher development, and (4) learner dispositions and SDL in engineering contexts. The findings suggest that SDL-STEM research is becoming increasingly interdisciplinary, technology-integrated, and pedagogically diverse. Despite growing interest, cross-regional collaboration remains limited. Future research should focus on inclusive partnerships and context-sensitive SDL implementation models to bridge global educational disparities.

Keywords: Self-Directed Learning, STEM education, Bibliometric analysis, Learning technologies, Research trends, 21st-century skills

1. INTRODUCTION

The rapid digital evolution has transformed education, introducing virtual classrooms and online platforms that enhance autonomy and access (Li et al., 2024; Means et al., 2014). This shift from teacher-centered to learner-centered models positions Self-Directed Learning (SDL) as essential for learners in flexible, personalized environments (Garrison, 1997; Voskamp et al., 2022).

SDL is a learner's capacity to plan, execute, and evaluate learning with minimal guidance (Knowles, 1975; Loyens et al., 2008), a critical skill for adaptive and continuous learning in the 21st century (Altinpulluk et al., 2023; Trúchly et al., 2019). Studies have linked SDL to higher motivation, engagement, and achievement, particularly in settings that encourage independent inquiry (Voskamp et al., 2022).

STEM education responds to global needs for innovation and sustainability (Marginson et al., 2013). Its interdisciplinary nature requires methods that combine content knowledge with higher-order skills and autonomy (Çubukcu, 2017; Moore et al., 2020). SDL intersects with STEM pedagogy, supporting self-regulation and independent learning in problem-based contexts (Davidoff & Piñeiro, 2017; Smith et al., 2022).

Research in STEM education has highlighted interventions such as project-based learning, flipped classrooms, and digital platforms as effective ways to promote learner independence (Chen, 2021; Öztöp, 2023).

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Virtual labs help students work at their own pace, reinforcing inquiry skills (Trúchly et al., 2019). However, the literature on SDL in STEM remains fragmented and often limited to specific interventions or educational levels (Asyhari & Sifa'i, 2021).

Although bibliometric studies exist for SDL (Oram et al., 2023) and STEM (Ha et al., 2020; Zhang et al., 2021), few systematically map SDL trends within STEM. This gap is notable as SDL becomes more integrated with STEM education frameworks. Mapping SDL's role in STEM is vital for practical instruction and policy (Donthu et al., 2021; Oya et al., 2024).

This study is grounded in Knowles' (1975) theory of andragogy, which emphasises learners' autonomy, readiness to learn, and problem-solving. It also draws from Garrison's (1997) SDL model, which highlights motivation, self-management, and self-monitoring. Together, these frameworks provide a comprehensive lens for understanding how SDL aligns with STEM learning contexts that require active, inquiry-driven, and reflective engagement.

This study conducts a comprehensive bibliometric analysis of SDL research in STEM education from 2005 to 2024. Bibliometric analysis quantitatively evaluates productivity, impact, and collaboration in a field, identifying emerging clusters and concept evolution (Donthu et al., 2021; Zupic & Čater, 2015).

This background leads to the study's main research question:

- What are the research trends of Self-Directed Learning within STEM education as evidenced by bibliometric data from 2005 to 2024?
- What are the dominant thematic clusters of Self-Directed Learning within STEM education as evidenced by bibliometric data from 2005 to 2024?
- What are the key contributing authors, institutions, and countries in the field of Self-Directed Learning within STEM education as evidenced by bibliometric data from 2005 to 2024?

2. METHOD

This study employed bibliometric analysis to examine research trends in Self-Directed Learning (SDL) within STEM education from 2005 to 2024. Bibliometric analysis is a quantitative method that evaluates scholarly literature through publication outputs, citation patterns, and intellectual linkages (Donthu et al., 2021; Zupic & Čater, 2015). This method identifies key contributors, thematic clusters, and emerging research fronts in the field.

2.1 Data Source and Search Strategy

The data were retrieved from Scopus, a leading citation and abstracting platform with broad coverage across education, engineering, the social sciences, and technology (Baas et al., 2020). Scopus was chosen for its reliability, rich metadata, and compatibility with bibliometric software

(Aksoy et al., 2024; Azwar et al., 2024; Sweileh, 2018; Turmuzi et al., 2023; Yusuf et al., 2025).

The search was conducted in January 2025, using the following Boolean query:

TITLE-ABS-KEY ("self-directed learning" OR "self-directed") AND ("STEM" OR "science AND technology" OR "engineering AND mathematics"). To ensure relevance to education, a subject-area filter for Social Sciences was applied. Additional inclusion criteria were: (a) publication years between 2005 and 2024, (b) article type as "Journal Article", (c) English language, and (d) final published stage.

This search initially produced 157 documents. Screening for relevance involved titles, abstracts, and keywords. Duplicates or off-topic entries were removed—the final sample comprised 40 documents for the bibliometric analysis. Detailed information about the selection process will be provided in the next section.

2.2 Selection Criteria and Quality Assurance

To ensure that the selected articles were methodologically relevant and aligned with the research objectives, explicit inclusion and exclusion criteria were defined. These criteria yielded a focused and representative dataset of publications that explore the intersection of SDL-STEM. Table 1 presents the criteria for selecting studies that directly engage both SDL and STEM in education and meet the standards of scholarly quality and accessibility. This was critical for filtering out literature that, although related to SDL or STEM alone, did not contribute to the conceptual or empirical understanding of their intersection.

The article selection adhered to the PRISMA 2020 guidelines (Page et al., 2021; see Figure 1). First, 157 documents were retrieved from Scopus using a Boolean query. After screening titles, abstracts, and keywords, 90 articles were excluded due to duplication, irrelevance, or failure to meet the set criteria (publication year, subject area, or format). Another 27 were excluded because they did not directly address the intersection of SDL and STEM education. In total, 40 articles remained for bibliometric analysis.

Table 1 Inclusion and exclusion criteria

Inclusion	Exclusion
The article explicitly addresses Self-Directed Learning (SDL) in the context of STEM education	Articles focusing solely on SDL or STEM without exploring their intersection
The study is empirical, conceptual, or review-based, and published in a peer-reviewed journal	Conference abstracts, non-peer-reviewed sources
The article was published between 2005 and 2024 in English	Articles without accessible bibliographic metadata

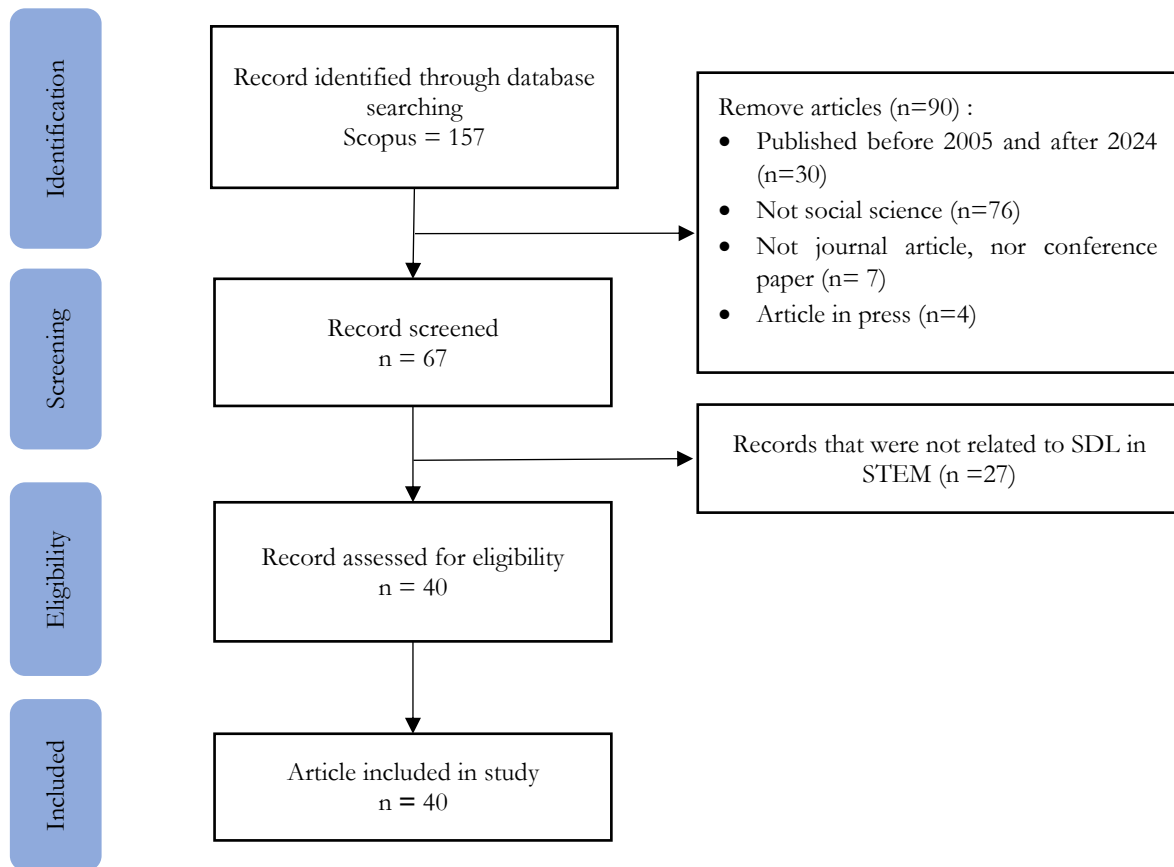


Figure 1 Article selection flowchart illustrating the systematic screening and inclusion process of SDL-STEM articles from the Scopus database

2.3 Data Processing and Analytical Tools

Bibliographic data were exported from Scopus in BibTeX and RIS formats and imported into RStudio using the Bibliometrix and Biblioshiny packages (Aria & Cuccurullo, 2017) for quantitative analysis. The analysis included annual scientific production, document types, authors, journals, countries, and institutions with the highest relevance. It also examined keyword co-occurrence networks, author collaboration networks, and international co-authorship networks. RStudio is an integrated development environment (IDE) for R. According to Kronthaler & Zöllner (2021), RStudio facilitates data importation, script writing, and saving work results—features that are particularly beneficial for novice users and students. Its user-friendly interface enables efficient, systematic management and analysis of bibliometric data.

Beyond being a tool for beginners, RStudio offers extensive statistical analysis capabilities, making it highly suitable for data-driven research. The platform supports a wide range of quantitative methods, including hypothesis testing, analysis of variance (ANOVA), and regression (Egoshin et al., 2018; Okoye & Hosseini, 2024). These capabilities make RStudio a valuable tool for constructing complex and measurable bibliometric mappings. Its

reliability in handling large datasets and complex information structures positions it as an ideal choice for empirical, data-intensive scientific research.

In addition to its statistical functions, RStudio excels in data visualization. As noted by Paquot & Larsson (2020), it supports various visualization techniques, including bar plots, histograms, and boxplots, which are essential for data exploration and presentation. Furthermore, RStudio can be integrated with advanced visualization tools such as D3.js and Tableau (Nair et al., 2019), enabling the creation of dynamic and interactive visualizations. The combination of R's analytical power and the sophisticated visual features of these tools broadens RStudio's applicability across multiple domains, including education, academic research, data journalism, and evidence-based decision-making.

Furthermore, VOSviewer (van Eck & Waltman, 2010) is an advanced software tool specifically designed to construct and visualize bibliometric networks, including citation relationships, bibliographic coupling, co-citation, and co-authorship. In this study, VOSviewer was employed to visualize keyword networks and to identify thematic clusters based on term co-occurrence. Its density and overlay visualization features were utilized to interpret the intellectual structure of the research field in greater depth. These capabilities enable researchers to observe patterns of

interconnectivity within the scientific literature and identify highly interactive or rapidly evolving thematic areas.

As a bibliometric analysis tool, VOSviewer has been widely adopted in scientometric studies and domain mapping due to its robust capacity to process large and complex datasets of literature. The software supports the construction of various network types, including citation networks, author collaboration networks, and keyword co-occurrence networks (Ampofo et al., 2024; Li & Wei, 2022; Tomaszewski, 2023). Its strength in generating detailed and intuitive visualizations makes VOSviewer especially valuable for researchers seeking to explore knowledge structures, research trends, and collaborative relationships among authors or institutions within a specific discipline.

The increasing popularity of VOSviewer is evident in the significant growth in the number of publications that utilize it as a primary tool in bibliometric analysis (Pan et al., 2018). In addition to offering high-quality visualizations, VOSviewer enables the creation of interactive maps that can be embedded in online platforms, thereby facilitating the digital analysis and interpretation of scientific data (Li & Wei, 2022). With its wide range of features and flexibility, VOSviewer not only enhances the outcomes of bibliometric studies but also provides comprehensive insights into the evolving dynamics of scientific knowledge across various disciplines.

2.4 Analytical Procedure

The analytical process involved five key steps, adapted from Donthu et al. (2021):

- Data Retrieval: Collecting bibliographic records using structured queries from Scopus.
- Data Cleaning: Removing irrelevant articles, duplicates, and errors in metadata.
- Performance Analysis: Identifying publication and citation patterns over time.
- Science Mapping: Constructing co-authorship, co-word, and citation networks.
- Visualization and Interpretation: Interpreting clusters, link strengths, and evolution of research themes.

Through this method, the study provides a comprehensive quantitative overview of SDL research trends in STEM education, revealing thematic orientations that inform the future research agenda.

3. RESULT AND DISCUSSION

3.1 Performance Analysis

The performance analysis provides a general overview of the bibliographic dataset retrieved from Scopus, focusing on the core metadata of publications addressing Self-Directed Learning (SDL) in STEM education between 2005 and 2024.

As shown in Table 2, 40 documents were identified over 20 years, reflecting modest but increasing scholarly interest in this interdisciplinary field. The annual growth rate of 9.35% suggests a relatively stable expansion in

research outputs, particularly in recent years, as digital learning environments and independent learning models have gained global momentum (Donthu et al., 2021).

In addition to publication and authorship patterns, a reference analysis was conducted to assess the depth of scholarly grounding in the selected studies. The 40 articles collectively cited 1,523 references, yielding an average of 38 per document. This indicates a substantial level of engagement with the literature, consistent with expectations for scholarly rigour in interdisciplinary research domains (Donthu et al., 2021; Zupic & Čater, 2015). The relatively high reference density suggests that researchers in SDL-STEM education aim to integrate diverse theoretical and empirical foundations, ranging from educational psychology to technology integration and STEM-specific pedagogy (Cobo et al., 2011). As noted in previous bibliometric studies, such reference patterns may reflect both the maturity of the research domain and the need for multidimensional perspectives (Ellegaard & Wallin, 2015). Based on this evidence, it is recommended that future research in SDL-STEM contexts maintain a minimum of 35-40 references per article to ensure sufficient grounding in the literature and comprehensive theoretical scaffolding.

The research output involved 127 authors, indicating a diverse and active scholarly community contributing to SDL-STEM discussions. Notably, only five documents were single-authored, while the average number of co-authors per document was 3.25, reflecting a collaborative research culture consistent with broader trends in educational technology and STEM education research (Zhang et al., 2021).

This collaborative pattern may also point to the interdisciplinary nature of SDL in STEM, requiring input from specialists in pedagogy, engineering education, digital learning, and cognitive psychology. Multidisciplinary collaboration is a defining feature of 21st-century research, significantly facilitating the exchange of diverse perspectives and integrating expertise from multiple domains (Ajakaye & Ogunniyi, 2021). This collaborative approach is especially pertinent to studies on SDL within STEM education, as these inherently require comprehensive insights into educational processes, technological integration, and scientific competencies. This

Table 2 Main information

Description	Results
Timespan	2005-2024
Documents	40
Annual Growth Rate (%)	9.35
Authors	127
Authors of Single-Authored Docs	5
Co-Authors per Doc	3.25
Average Citation per Doc	11.75
Number of references	1,523

observation aligns with a consistent trend observed over the past two decades, in which SDL-STEM research has increasingly emphasized collaborative methodologies.

3.2 Development and Progress of STEM Self-Directed Learning in STEM Education Research

The temporal analysis of publication output, illustrated in Figure 2, reveals the evolution of scholarly interest in the intersection of Self-Directed Learning (SDL) and STEM education from 2005 to 2024. The early years (2005–2015) show sporadic and minimal publication activity, indicating that SDL in STEM had not yet gained significant academic traction during that period. This aligns with broader trends in education research, where SDL was still primarily associated with adult learning and higher education rather than being fully integrated into STEM-focused pedagogical frameworks (Garrison, 1997; Loyens et al., 2008).

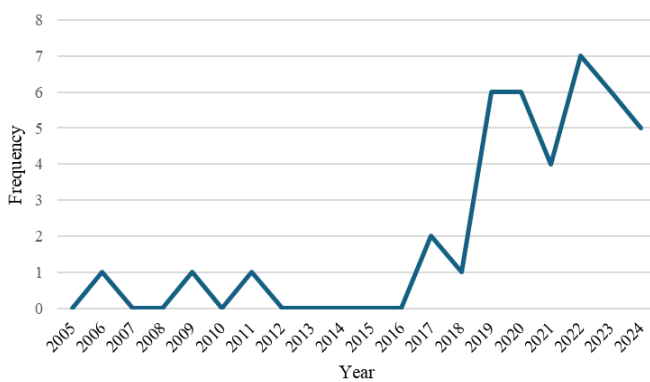


Figure 2 Annual scientific production

A turning point appears around 2016, marked by a gradual but consistent increase in publication frequency. The most notable surge occurred between 2018 and 2023, reflecting an intensified global focus on learner autonomy, digital learning tools, and STEM literacy amid the rise of remote learning initiatives accelerated by the COVID-19 pandemic (Altinpulluk et al., 2023; Zawacki-Richter & Bozkurt, 2023). During this period, SDL began to be integrated into emerging STEM learning environments such as flipped classrooms, project-based learning, and virtual laboratories—each of which emphasised student agency and personalised learning paths (Chen, 2021; Trúchly et al., 2019).

The highest number of publications was recorded in 2023, with seven documents, followed by a slight decline in 2024. This minor decrease may reflect a stabilisation of the research field or a redirection of scholarly attention toward more specialised subtopics within SDL-STEM integration, such as motivation, equity, and curriculum adaptation (Dancy & Hodari, 2023; Öndeş, 2025).

Overall, this growth trajectory indicates that SDL in STEM has transitioned from a niche topic to an emerging research domain with interdisciplinary relevance. The increased scholarly attention in recent years suggests a growing consensus on the importance of fostering

independent learning competencies in STEM fields, particularly in response to global shifts in educational delivery and assessment models (Donthu et al., 2021; Oya et al., 2024).

3.3 Research Contributors and Collaboration Network

Geographic Distribution of Research

The geographic distribution of corresponding authors reflects the global landscape of research on Self-Directed Learning (SDL) in STEM education. As shown in Figure 3, the United States is the most significant contributor, followed by Australia, Canada, and several countries in Asia and Europe.

The United States leads in the number of documents authored, reflecting the country's consistent investment in educational innovation and its strong research infrastructure across both SDL and STEM education. This dominance is supported by national initiatives promoting digital learning, STEM competencies, and 21st-century learning skills. Educational policy trajectories in countries characterised by dominant leadership often reflect the political vision of national leaders, thereby permeating bureaucratic structures and shaping the emergence of educational research priorities (Levy, 2022). Conversely, evidence from countries such as Sweden shows that when researchers and policymakers operate within a shared framework of values, public policies become more closely aligned with research findings. Consequently, research agendas evolve to better align with policy demands. These dynamics underscore the influential role of interactions between national policy frameworks and research orientations in shaping the global landscape of SDL-STEM research.

Australia and Canada also emerged as significant contributors. Both countries have emphasized personalized learning pathways and the integration of technology in education, which are foundational to SDL frameworks. These countries have also been active in exploring pedagogical approaches such as inquiry-based STEM learning, project-based models, and blended instruction—often with embedded self-directed learning components (Chen, 2021).

Notably, Indonesia appears in the top five, highlighting the growing relevance of SDL in emerging economies, particularly in the context of the digital transformation of education. Recent government policies and international collaborations may have contributed to this upward trend in Indonesian SDL-STEM research outputs (Aksnes & Sivertsen, 2023).

The presence of countries such as Thailand, the Philippines, Saudi Arabia, and the Netherlands further demonstrates the global spread of interest in SDL. Although publication counts from these nations remain relatively modest, their inclusion highlights the expanding geographic scope of SDL-STEM research, particularly in the Global South. Researchers in these regions frequently

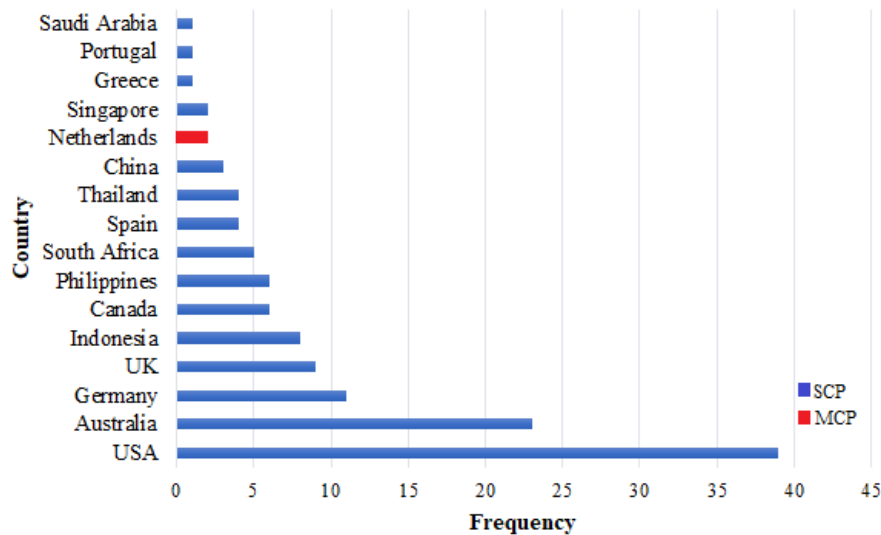


Figure 3 Corresponding authors' countries

encounter challenges stemming from historical colonial legacies, resource limitations, and the dominance of foreign languages within global academic discourse, all of which can impede the autonomous creation and dissemination of local knowledge (Gueye et al., 2022). Additionally, power imbalances inherent to North-South research partnerships often position researchers from the Global South as technical implementers rather than equal intellectual collaborators. This dynamic constrains epistemic autonomy and the development of local research capacities (Ansoms et al., 2024). Consequently, international research collaborations must embody principles of equity and mutual empowerment to advance the global SDL-STEM research agenda effectively.

The collaboration pattern is also evident in the color coding in Figure 3, where SCP (Single Country Publications) dominates in most countries. At the same time, MCP (Multiple Country Publications) is observed notably in the Netherlands, suggesting active cross-national research engagement. This aligns with calls in the literature for increased international research cooperation to address global education challenges and enrich comparative SDL-STEM perspectives (Donthu et al., 2021; Zupic & Čater, 2015).

These patterns collectively underscore the necessity of sustained, inclusive global dialogue to design STEM education informed by SDL, ensuring it is adaptable across diverse educational systems and cultural contexts. Perceptions of teaching effectiveness can also vary considerably based on students' cultural backgrounds. Cultural dimensions, such as power distance and individualism, significantly shape learners' interpretations and expectations of educational experiences (Arnold & Versluis, 2019). Thus, fostering cross-cultural awareness is crucial in developing practical and inclusive pedagogical approaches. Instructors' teaching methodologies in higher

education contexts often reflect their national cultural values and the educational systems within which they operate (Hecht & Kahrens, 2021). As SDL frameworks become increasingly prevalent globally, recognizing and accommodating cultural diversity in instructional design will be essential for their successful implementation.

Primary National Contributors

Table 3 presents the ten most productive and most cited countries in the field of SDL-STEM. These data serve analytical entry points for understanding the geographical distribution of intellectual leadership, research investment, and scholarly influence in this emerging interdisciplinary domain. Identifying which countries are driving the discourse can inform decisions around collaboration, benchmarking, and research alignment.

The prominence of countries—both in terms of quantity and citation impact—suggests a sustained institutional commitment to SDL-STEM research. This concentration of high-impact scholarship points to established academic ecosystems that actively shape

Table 3 Primary national contributors

Country rank	Country	Number of Articles	Country	Number of Citation
1	USA	39	USA	138
2	Australia	23	Australia	92
3	Germany	11	Canada	78
4	UK	9	UK	21
5	Indonesia	8	Thailand	18
6	Canada	6	Saudi Arabia	15
7	Philippines	6	Singapore	8
8	South Africa	5	Germany	7
9	Spain	4	Spain	7
10	Thailand	4	Netherlands	5

theoretical development and empirical practices in SDL-STEM studies.

The dual dimensions of productivity (number of publications) and influence (citation count) allow for a more granular analysis of research development. A country with modest output but high citation rates may indicate niche leadership or methodological innovation. In contrast, high productivity with limited citation impact may point to emerging but under-recognized research efforts. This nuance is essential for mapping the global intellectual structure of SDL-STEM, identifying gaps, and envisioning more equitable and distributed pathways for future scholarship.

Furthermore, early-stage scholars or institutions seeking to develop capacity in SDL-STEM may benefit from engaging with this global knowledge infrastructure, drawing on existing theoretical models, adapting methodological innovations, or forming cross-national research partnerships.

As expected, the United States ranks first in both dimensions, with 39 articles and 138 citations, confirming its leading role in driving SDL-STEM scholarship. This dominance aligns with previous bibliometric findings in educational technology and STEM research, where U.S. institutions often serve as knowledge hubs and centers for innovation (Donthu et al., 2021; Zhang et al., 2021).

Australia follows closely with 23 articles and 92 citations, reaffirming its position as a global frontrunner in implementing SDL pedagogies within STEM-based curricula. Australia's educational reforms and digital transformation initiatives may explain this high performance (Marginson et al., 2013).

Interestingly, Germany, the UK, and Canada also feature prominently, with Germany contributing 11 articles, Canada receiving 78 citations, and the UK showing a balanced presence in both publication and citation metrics. These countries are known for their strong research infrastructures and policy-level emphasis on science and engineering education (Moore et al., 2020).

A notable trend is the emergence of Indonesia and the Philippines as regional contributors, with 8 and 6 articles, respectively. Indonesia's presence suggests increased scholarly engagement with SDL concepts, particularly in higher education contexts and STEM teacher-training programs (Asyhari et al., 2023). While these countries are not yet highly cited, their growing output signals potential for future regional influence, especially with targeted investment in research visibility and international collaboration.

On the citation side, Thailand (18 citations) and Saudi Arabia (15 citations) appear despite having fewer publications, which may reflect the presence of highly cited individual works or international collaborative projects (Zupic & Čater, 2015). Singapore, Germany, and Spain

contribute moderate citation counts, rounding out the top 10 most-cited nations.

This data illustrates a combination of established global research powers and emerging contributors shaping the field of SDL in STEM. The dual metrics of productivity and citation offer a nuanced understanding of national research influence, suggesting that quantity does not always equate to impact—highlighting the need for quality-focused, collaborative, and contextually grounded research moving forward.

Leading Publication Sources, Institutions, and Researchers

To understand the epistemic structure and scholarly engagement within the field of Self-Directed Learning (SDL) in STEM education, this study analyzed the most relevant sources, institutional affiliations, and contributing authors. The analysis reveals that the most prominent publication venues are concentrated in interdisciplinary educational research and engineering education. Sources such as the Frontiers in Education Conference, Education Sciences, the Journal of Chemical Education, and the Australian Educational Researcher are among the most frequently used platforms for disseminating research in this domain. The inclusion of proceedings from technology-focused conferences, such as the Computer-Supported Collaborative Learning Conference (CSCL) and the IEEE World Engineering Education Conference, underscores the growing relevance of SDL within the discourse on digital learning and engineering education. These findings align with global shifts toward inquiry-based, student-centered STEM pedagogy, particularly in response to the integration of technology into instructional practice. Inquiry-based pedagogical approaches have become central to global reforms in science education, mainly because they actively engage students in scientific inquiry rather than traditional, passive, lecture-oriented instruction (Morris, 2025).

The global shift toward STEM education is primarily driven by the imperative to develop a workforce capable of addressing complex 21st-century challenges, positioning STEM as a critical element of knowledge-based economic development strategies in numerous countries (Kayan-Fadlelmula et al., 2022). Indeed, various educational jurisdictions have implemented integrated STEM curricula that have demonstrated significant benefits, including enhanced student engagement, stimulated creative problem-solving, and cultivated essential global competencies required for future personal and professional success (DeCoito, 2024). The increasing prominence of SDL models aligns seamlessly with these broader educational transformations.

Institutionally, the most active contributors to the literature include Monash University and Charles Sturt University in Australia, as well as Centro Universitario de la Defensa in Spain and East Carolina University in the United States (Table 4). These institutions are recognized for their emphasis on educational innovation and their international collaborations, particularly in curriculum development, STEM teacher education, and technology-enhanced learning. The presence of Franklin W. Olin College of Engineering and Purdue University further confirms the strong role of engineering-focused institutions in advancing research on SDL. Notably, Universitas Lampung in Indonesia is also featured among the most relevant affiliations, indicating emerging contributions from Southeast Asia and the increasing visibility of research originating from doctoral programs in science and education. Research productivity in higher education institutions is significantly influenced by factors such as institutional support for collaborative scholarship, funding availability, and conducive work environments that empower faculty to pursue research (Uwizeye et al., 2021) actively. Departments characterized by participatory organizational cultures and management practices rooted in mutual commitment typically exhibit higher research productivity compared to those constrained by rigid bureaucratic structures and limited academic autonomy (Edgar & Geare, 2013). These insights underscore the need to strengthen institutional capacities to increase research output from developing academic regions.

At the individual level, the most relevant authors represent a geographically and disciplinarily diverse group, including Dino Cubela, Pakon Ko, Pascal Neis, Vaicheslav Adamchuk, Modi Owied Al Moteri, Ameerbakhsh Omair, Clark I. Andersen, Nicholas Andronicos, Elena Arce-Fariña, and Jhun Matthew Ares. While no single scholar dominates the field, the distribution of authorial contributions indicates a collaborative, dispersed scholarly network, typical of interdisciplinary, practice-driven domains such as SDL in STEM. These authors contribute

to various thematic strands, including instructional design, motivation in engineering education, digital assessment, and learner autonomy. The diversity of institutional and national contexts represented by these authors reflects the field's global and multi-sectoral nature. STEM education today has evolved into an interdisciplinary framework with significant global implications. Beyond merely enhancing proficiency in scientific and technological subjects, it serves as a nexus that integrates various sectors by emphasizing the practical application of analytical, collaborative, and innovative competencies in real-world scenarios (Marzuki et al., 2024). The diversity of scholars and their varied backgrounds in this research domain highlights the inherently interconnected, practice-oriented nature of SDL within STEM fields. This diversity further underscores the growing recognition of SDL-STEM as a transformative educational approach across global higher education contexts.

Taken together, these patterns suggest that SDL research in STEM is being developed across a variety of knowledge platforms and institutional contexts. The field draws on expertise from both traditional education faculties and applied science institutions, illustrating its relevance not only for theoretical exploration but also for pedagogical reform and technological integration.

International Collaboration Networks

The international collaboration network in Figure 4 reveals two prominent clusters among countries contributing to SDL-STEM research. The first cluster is anchored by the United Kingdom, with Portugal and Greece forming tightly linked nodes—indicating a



Figure 4 International collaboration network

Table 4 Top contributors by categories

Most relevant sources	Most relevant affiliations	Most relevant authors
Proceedings - Frontiers in Education Conference, FIE Education Sciences	Monash University	Cubela, Dino
Computer-Supported Collaborative Learning Conference, CSCL	Centro Universitario De La Defensa	Ko, Pakon
Journal Of Chemical Education	Charles Sturt University	Neis, Pascal
2023 IEEE 2nd German Education Conference, Gecon 2023	East Carolina University	Adamchuk, Vaicheslav
Australian Educational Researcher	Franklin W. Olin College of Engineering	Al Moteri, Modi Owied
Computer Applications in Engineering Education	Oakland University William Beaumont School of Medicine	Ameerbakhsh, Omair
Disciplinary and Interdisciplinary Science Education Research	Program Studi Doktor Pendidikan Fakultas Keguruan dan Ilmu Pendidikan Universitas Lampung	Andersen, Clark I.
Early Childhood Education Journal	Purdue University, West Lafayette	Andronicos, Nicholas
Edunine 2022 - 6th IEEE World Engineering Education Conference	University of Stirling Mainz	Arce-Fariña, Elena
	University Of Applied Sciences	Ares, Jhun Matthew

concentrated pattern of co-authorship and research alignment. The UK's centrality in this cluster suggests its role as a coordinating node that not only facilitates collaboration but also influences the thematic and methodological direction of research within the group. Within the SDL-STEM framework, such collaborative structures carry significant epistemic implications.

Countries embedded in dense research networks often exhibit greater capacity to experiment with and disseminate instructional models that promote learner autonomy, metacognitive regulation, and problem-based inquiry in STEM settings. The co-authorship intensity observed here may reflect a shared pedagogical orientation toward constructivist STEM learning environments where self-directed learning is not merely an individual trait but an outcome deliberately cultivated through curriculum design.

Furthermore, the regional coherence of this cluster—likely situated within broader policy infrastructures such as the European Higher Education Area (EHEA)—suggests that SDL is being operationalized through transnational educational reforms. These reforms often emphasize active learning, student agency, and cross-disciplinary integration, all of which are foundational to SDL-STEM research. Programs such as Erasmus+ or Horizon Europe (Zupic & Čater, 2015) may support not just the logistics of collaboration, but also the co-construction of knowledge frameworks that inform classroom-level practices.

The second cluster includes Germany and the Netherlands, with Germany emerging as a significant hub of collaboration in the SDL-STEM research landscape. The visual density and node size associated with Germany indicate both a strong research presence and active participation in multi-country projects. These two countries are recognised for their long-standing investments in technical and engineering education, as well as their leadership in integrating digital learning into STEM curricula (Donthu et al., 2021; Oya et al., 2024).

Collaborative projects between Germany and the Netherlands are frequently embedded in EU-funded frameworks, such as Horizon 2020, Next-Lab, and Go-Lab, which emphasise inquiry-based science learning, metacognitive scaffolding, and the application of learning analytics in adaptive systems (Pedaste et al., 2017). The Netherlands, with institutions like the University of Twente and Delft University of Technology, plays a key role in developing online laboratories and AI-supported platforms. Germany, on the other hand, contributes expertise in STEM didactics, vocational training, and large-scale implementation of digital pedagogies. These partnerships demonstrate a shared commitment to enhancing self-directed and technology-driven learning across diverse educational settings. Their collaboration not only supports the dissemination of innovative pedagogical models across Europe but also contributes to capacity-building for digital competencies in STEM education.

The overall structure of the collaboration network suggests that while global engagement with SDL-STEM topics is growing, it remains relatively regionalised, with European countries forming the most active clusters. Notably absent from the network visualisation are countries such as the United States, Australia, and Indonesia, despite their high publication output. This suggests that much of the research from these regions may be conducted in domestic contexts or within national teams, limiting cross-national knowledge exchange.

The current structure of international collaboration presents both opportunities and challenges. While existing clusters demonstrate the benefits of regional synergies, there remains significant potential to foster broader transnational cooperation. Enhancing global collaboration—particularly by connecting high-output yet structurally isolated research systems—would enrich comparative perspectives and accelerate innovation in SDL-STEM education across diverse educational settings.

To advance this goal, future research agendas and international funding bodies (e.g., Horizon Europe, Erasmus+, UNESCO's Global Education Coalition) should explicitly support the formation of intercontinental research consortia, joint publication agreements, and long-term capacity-building programs. Furthermore, international conferences and special issues in high-impact open-access journals should be leveraged as strategic platforms to promote global visibility, interdisciplinary dialogue, and cross-regional dissemination (European Commission, 2023; UNESCO, 2021)

These measures can bridge geographic and epistemological gaps in the SDL-STEM research landscape, contributing to the development of globally relevant, locally adaptable pedagogical models that align with UNESCO's 2030 Education Agenda and the European Education Area's strategic objectives.

3.4 Research Trends and Predominant Themes

Network Analysis of Research Keywords

Keyword co-occurrence analysis is a central component of bibliometric mapping, as it reveals the conceptual structure of a research domain. The size of nodes and the thickness of connecting lines in network visualisations signify the prominence and strength of relationships among various elements. Larger nodes and thicker lines indicate greater conceptual relevance and stronger associations between terms within the research analysed (van Eck & Waltman, 2010). The connecting lines represent relationships based on co-occurrence or other bibliometric associations, while proximity between items on the visualisation map indicates thematic relatedness. Items positioned closer together are conceptually more similar (van Eck & Waltman, 2013). Comprehending this visualisation structure enables researchers to more effectively discern and interpret the conceptual landscape of SDL in STEM education.

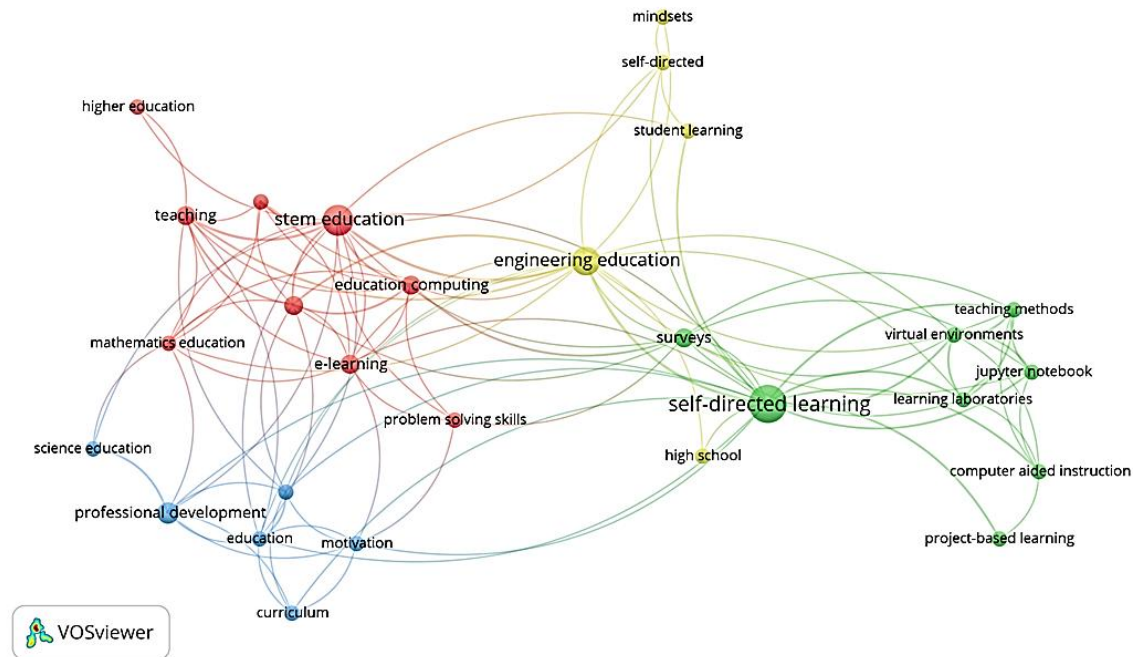


Figure 5 Keyword network visualization

Using the VOS viewer, 29 frequently occurring author keywords (with at least five occurrences) were visualised, resulting in the keyword network shown in Figure 5. In this network, each node represents a keyword, while the lines connecting them indicate the strength of co-occurrence—how often two keywords appear together in the same article. Keywords that frequently co-occur are grouped into the same cluster and represented with the same colour, signifying thematic closeness.

The central position of self-directed learning confirms its status as the core research construct within the network. This term is closely linked to keywords such as student learning, engineering education, project-based learning, and virtual environments, underscoring its embeddedness in broader discussions of learner-centred approaches in STEM contexts. The density and connectivity of the network also suggest a high level of thematic integration across clusters, indicating that SDL research in STEM is not only expanding but also becoming more complex.

Figure 5 shows five distinct clusters, each representing a different sub-theme within the SDL-STEM discourse. These clusters and their dominant keywords are further analysed and categorised in Table 5, which provides a detailed overview of the conceptual trends shaping the field.

The presence of diverse but interconnected keywords across clusters reinforces the interdisciplinary nature of SDL in STEM education. The co-occurrence analysis reveals that several keywords are not only thematically relevant but also closely aligned with the actual research focus of the analysed documents. For instance, terms such as motivation, curriculum, and professional development

frequently appear in studies exploring how self-directed learning supports students' intrinsic engagement, curriculum adaptation in STEM fields, and teacher competencies in fostering learner autonomy. These keywords indicate a strong linkage between educational psychology and instructional design within SDL-based STEM learning environments. Additionally, keywords such as e-learning, engineering education, and computer-aided instruction are prominent in publications that investigate the integration of digital tools and platforms to support personalised, flexible, and interactive STEM learning. This reflects a growing trend of embedding self-directed learning strategies into technology-enhanced pedagogy, particularly in engineering and computer science education. Thus, the emergence of these keywords underscores both the conceptual and applied dimensions of SDL within the evolving discourse of STEM education. Such connections reveal the multidimensional aspects of SDL research and underscore the importance of synthesising pedagogical, technological, and cognitive perspectives in future studies. Research in SDL-STEM emphasises the essential integration of learning theories and instructional design strategies, acknowledging that SDL's effectiveness depends on learners' cognitive and affective self-regulation throughout the learning process (Mercado, 2024). Furthermore, technologically enriched learning environments that incorporate inquiry-based and collaborative pedagogical practices have proven particularly beneficial in fostering SDL. These environments enhance learner autonomy, build digital competencies, and encourage active student engagement

Table 5 Research cluster

Number of Clusters	Number of Keywords	Component Keywords
1	9 items	E-learning, education computing, higher education, learning systems, mathematics education, modulars, problem-solving skills, STEM education, teaching
2	7 items	Computer-aided instruction, Jupyter notebook, learning laboratories, project-based learning, self-directed learning, surveys, teaching methods, virtual environments
3	6 items	Curriculum, education, motivation, problem-based learning, professional development, and science education
4	5 items	engineering education, high school, mindsets, self-directed, student learning

through project-based learning and authentic, real-world problem-solving activities (Pedaste et al., 2017). Consequently, the successful implementation of SDL in STEM contexts is closely tied to the deliberate construction of educational ecosystems that address both the cognitive demands and technological advancements characteristic of 21st-century learning.

Emergent Research Clusters

Table 5 summarises the thematic clusters identified through keyword co-occurrence analysis using VOS viewer. These clusters represent the intellectual structure of Self-Directed Learning (SDL) research within the STEM education context, illustrating the evolving directions and thematic priorities in the literature. A total of four clusters were extracted, each comprising multiple interrelated keywords that point to distinct, yet overlapping, areas of inquiry.

The first and largest cluster comprises keywords such as e-learning, education computing, higher education, learning systems, mathematics education, modular learning, problem-solving skills, STEM education, and teaching. This cluster represents the dominant theme in SDL-STEM research, reflecting how technology-driven instructional models support learner autonomy. As noted by Asyhari et al. (2023), current research trends focus on how technological interventions support SDL across various educational levels. E-learning, in particular, has emerged as a key enabler of SDL, especially amid the global transition to online learning during the COVID-19 pandemic (Van Nuland et al., 2020).

The presence of the keyword higher education suggests that SDL in STEM is still predominantly studied in tertiary education contexts, where learners possess more developed metacognitive and self-regulatory skills (Asyhari et al., 2023). Nonetheless, the emphasis on teaching within this cluster implies that instructors play a critical role in scaffolding and facilitating SDL, highlighting a potential area for teacher training and pedagogical reform.

Moreover, the inclusion of mathematics education and problem-solving highlights the relationship between these constructs and SDL in STEM. As reported by Jordaan & Havenga (2020), students develop SDL competencies when introduced to problem-solving in mathematics. This is supported by a study by Chen (2021), which found that integrating inquiry-based STEM curriculum principles and

student-relevant issues, while connecting various subject areas, enables integrated learning and systematically designed self-directed learning (SDL) activities. These approaches encourage students to apply their knowledge in solving real-world problems and enhance their creative thinking skills. Therefore, well-designed problem-solving activities can effectively support SDL within STEM education.

The cluster also suggests a future research agenda to optimise digital teaching environments and enhance problem-solving and autonomous learning in STEM disciplines. For instance, Gumbi et al. (2024) advocate for the use of digital STEM games to support contextualised SDL in sustainability education within higher education.

The second cluster consists of keywords such as computer-aided instruction, Jupyter Notebook, learning laboratories, project-based learning, self-directed learning, surveys, teaching methods, and virtual environments. This cluster explores the intersection between SDL and cutting-edge pedagogical models, particularly those facilitated by educational technologies. There is a strong representation of digital and simulation-based tools that enable students to engage in exploratory, inquiry-based learning. Yunzal et al. (2024) emphasise the importance of active learning strategies, such as project- and problem-based learning, which support student autonomy in virtual settings.

The keywords "learning laboratories" and "project-based learning" are evident in the study by Doughan & Shahmuradyan (2022), which describes a second-year analytical chemistry lab that incorporated real-world experiment design to boost early interest in STEM. Combined with inquiry-based teaching, this method supports 21st-century skills, including SDL. This cluster highlights opportunities to expand research on the effectiveness of technology-supported instructional strategies in flexible learning environments (e.g., virtual classes, modular approaches, and blended learning) to foster SDL competencies in various STEM contexts (Öztop, 2023).

Moreover, the frequent occurrence of surveys as a keyword suggests that much of the SDL-STEM research in this domain is driven by empirical, cross-sectional studies, as supported by bibliometric trends in Southeast Asia (Ha et al., 2020). This cluster highlights a clear opportunity to advance research on the effectiveness of different

technology-integrated strategies in promoting SDL competencies across diverse STEM contexts (Öztop, 2023).

The third cluster includes curriculum, education, motivation, problem-based learning, professional development, and science education. This thematic area underscores the importance of curriculum design in fostering SDL. The growing demand for STEM expertise, driven by technological advances, has prompted curricular reforms that emphasise critical thinking and communication skills. Higher education institutions are responding by adopting methods such as project-based learning, course-based undergraduate research experiences (CURE), and process-oriented guided inquiry learning (POGIL) (Doughan & Shahmuradyan, 2022).

The presence of PBL—albeit with a smaller node size—reflects its growing relevance as a pedagogical bridge between interdisciplinary content and autonomous learning (Smith et al., 2022). Problem-based approaches place students in charge of their knowledge and learning process (Flores, 2018). The integration of PBL in STEM clusters enhances student motivation and autonomy, aligning with transformative, student-centred learning approaches (Simanjuntak et al., 2022). Furthermore, PBL supports the development of undergraduate students' epistemological beliefs about STEM (Lee et al., 2023). Prior research has also shown that PBL, when integrated with digital learning environments and gamification, can enhance student motivation and performance in STEM education (Boom-Cárcomo et al., 2024).

Motivation emerges as a central construct in this cluster, with studies showing a reciprocal relationship between SDL and motivation. Motivation is essential for students to develop SDL skills (Keebler & Huffman, 2020), and in turn, SDL can enhance student motivation (Stolk et al., 2006). However, Stolk et al. (2006) also note that SDL may sometimes lead to student frustration and dissatisfaction. They further highlight the importance of understanding both the outcomes and causes of students' responses to SDL—both positive and negative.

Given the crucial role of teachers in STEM education, the development of teacher competencies to foster SDL is increasingly emphasised, as reflected in the prominence of the keyword professional development. According to Weinberg et al. (2021), high-quality STEM teacher education relies on well-prepared educators who can design compelling learning experiences, provide targeted feedback, mentor teachers throughout their careers, and conduct rigorous research to advance theory and practice in education. In addition, future research may benefit from exploring curriculum design that integrates motivational factors and learner autonomy, particularly within technologically enriched STEM environments.

The fourth cluster centres on keywords such as engineering education, high school, mindsets, self-directed learning, and student learning. The prominence of

engineering education as a node reflects sustained scholarly attention to integrating SDL principles in technical disciplines (Le Thi Tuyet et al., 2024). Notably, the presence of high school suggests a gradual shift in research interest toward younger learners, even though SDL has historically been associated with higher education. Earlier studies have also identified gaps in fostering SDL among younger students (Asyhari et al., 2023), presenting new opportunities to explore how SDL can be developed at the secondary level—particularly in STEM pathways where autonomous learning habits are critical for long-term academic and professional success.

The keywords "self-directed mindset" and "student learning" highlight the interconnection among these constructs. Flores (2018) found that SDL is a challenging yet rewarding experience, with students feeling respected and trusted even if not fully supported in teacher-directed classroom settings. Moreover, problem-based science learning not only enhances students' independent problem-solving skills but also encourages them to adopt the mindset and habits of scientists and inventors—contributing to early identity formation in STEM fields (Flores, 2018).

In conclusion, these four clusters collectively reveal a multifaceted research landscape, ranging from macro-level curriculum reform to micro-level digital tool integration. The emergence of distinct clusters also suggests that SDL in STEM is evolving from a conceptual framework into a practical, researchable educational model. Further research is warranted to examine cross-cluster linkages.

4. CONCLUSION

Based on a bibliometric analysis of the literature on Self-Directed Learning (SDL) in STEM education from 2005 to 2024, several key conclusions can be drawn. First, the publication trend demonstrates consistent growth, particularly after 2018, with an average annual growth rate of 9.35%. Although the total number of publications remains modest ($n = 40$), the upward trajectory suggests an increasing scholarly interest in SDL in technology-enhanced STEM contexts. Most studies focus on higher education settings, although there is a growing interest in exploring SDL implementation at the secondary level, particularly in response to the transition to digital learning following the COVID-19 pandemic. Second, the keyword co-occurrence analysis identified four primary thematic clusters that shape the conceptual landscape of SDL-STEM research. These clusters reflect key areas of integration: digital tools, pedagogical innovation, curriculum support, and learner mindset—all of which play significant roles in shaping STEM education practices in SDL. Third, the analysis reveals that countries such as the United States and Australia are among the most active in terms of publication volume. At the same time, Germany and the Netherlands make significant contributions to

international collaboration. Monash University and Charles Sturt University emerged as key institutional contributors. Authorial contributions are notably dispersed, suggesting a collaborative yet decentralised research field. While international collaboration is on the rise, it remains concentrated mainly in Europe, with limited cross-regional engagement—particularly from Southeast Asia—despite promising contributions from emerging countries such as Indonesia and the Philippines.

5. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While this study provides a comprehensive bibliometric overview of research trends in Self-Directed Learning (SDL) within STEM education from 2005 to 2024, several limitations should be acknowledged to inform future research trajectories. First, this study is confined to documents indexed in the Scopus database, which, although widely recognised for its academic breadth and metadata quality, may not encompass relevant publications indexed in alternative repositories such as Web of Science, ERIC, or Google Scholar. This limited scope may have excluded influential grey literature or emerging works published in non-indexed regional journals. Future studies are encouraged to adopt a multi-database strategy to enhance comprehensiveness and cross-validation of trends.

Second, the bibliometric data analysed are primarily quantitative, relying on publication counts, citation metrics, and keyword co-occurrence. While such metrics reveal structural patterns, they cannot fully capture the depth of conceptual development or theoretical nuance within the SDL-STEM discourse. Qualitative content analysis or systematic literature review approaches could complement bibliometric results to provide richer interpretations of key themes, theoretical frameworks, and methodological paradigms.

Third, although this study employed co-word and co-authorship analyses to identify collaborative patterns and thematic clusters, the analysis did not incorporate advanced network metrics (e.g., betweenness centrality, PageRank, or eigenvector centrality), which could offer more profound insight into the positioning and influence of specific authors, institutions, or countries within the research network. Incorporating such enrichment tools may yield a more granular understanding of knowledge diffusion in future research.

Fourth, the keyword-based clustering may have been constrained by the variability in authors' terminology. Differences in keyword choice (e.g., “SDL” vs. “autonomous learning”) may lead to fragmentation in cluster construction. Future studies should consider thesaurus-based normalisation or manual refinement of keywords to improve semantic precision.

Lastly, the study's temporal scope, ending in early 2024, may not capture the most recent shifts driven by generative

AI, adaptive learning platforms, or sustainability-oriented STEM curricula. As the field rapidly evolves, continuous bibliometric monitoring using rolling windows (e.g., 5-year periods) is recommended to track emerging technologies and global educational disruptions.

In light of these limitations, future research should:

- Expand data sources to include a diverse set of indexing platforms.
- Integrate mixed-method approaches for deeper insights.
- Apply enriched bibliometric techniques and network algorithms; and
- Investigate the intersection of STEM with emerging domains, such as sustainability education, AI-driven personalisation, and global equity in science learning, through the lens of SDL.

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