Research article

Convergence of entrepreneurship and STEM Education: Trends and perspectives

Laurence C. Espino[1],*, Camille L. Espino[2], Ronilo P. Antonio[2], Jovita E. Villanueva[2] and Lilibeth DG. Antonio[3]

[1] College of Business Education and Accountancy, Bulacan State University, Philippines; laurence.espino@bulsu.edu.ph

[2] College of Professional Teacher Education, Bulacan State University, Philippines; camille.espino@bulsu.edu.ph, ronilo.antonio@bulsu.edu.ph, jovita.villanueva@bulsu.edu.ph

[3] College of Information and Communications Technology, Bulacan State University, Philippines; lilibeth.antonio@bulsu.edu.ph

* Correspondence: Email: laurence.espino@bulsu.edu.ph.

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Abstract: This study examines the convergence of entrepreneurship and science, technology, engineering, and mathematics (STEM) education, addressing the growing need to equip learners with technical expertise and entrepreneurial competencies for innovation-driven economies. Specifically, it aims to map the intellectual structure, research trends, and emerging themes that shape this interdisciplinary field. A bibliometric research design was employed using 174 peer-reviewed journal articles retrieved from the Scopus database (2002–2024). The analysis integrated performance analysis and science mapping techniques, including bibliographic coupling and co-word analysis, to identify conceptual relationships and future research directions. VOSviewer and Biblioshiny were utilized for data visualization and network mapping. Results reveal a steady growth in publications and citations since 2015, reflecting increasing scholarly interest in integrating entrepreneurial learning with STEM education. Four thematic clusters were identified, highlighting socio-technical and sustainability-oriented foundations, experiential curriculum integration, teacher- and competency-centered E-STEM models, and institutional mechanisms that shape entrepreneurial readiness in STEM education. Co-word analysis further emphasized engineering education, innovation, and entrepreneurship education as central research nodes, with emerging directions involving artificial intelligence (AI), sustainability, and digital transformation. The study highlights

the importance of education systems incorporating experiential, interdisciplinary, and technology-driven pedagogies to foster entrepreneurial mindsets and sustainable innovation among STEM learners. Overall, this research contributes by offering a methodologically integrated bibliometric mapping of the convergence between entrepreneurship and STEM education, utilizing a 22-year dataset, multi-technique clustering, and an explicit query design.

Keywords: entrepreneurship education, STEM education, innovation, bibliometric analysis, interdisciplinarity, experiential learning, sustainability, quality education

1. Introduction

The global education landscape is undergoing a profound transformation as societies confront rapid technological advancement, economic uncertainty, and pressing sustainability imperatives. In response, the integration of entrepreneurship and science, technology, engineering, and mathematics (STEM) education has emerged as a strategic approach for preparing learners for innovation-driven economies and evolving workforce demands [1,2]. Entrepreneurship education is commonly understood as a structured pedagogical process that develops learners' capacities to recognize opportunities, create value, and engage in innovation-oriented problem-solving across diverse contexts [3]. STEM education, by contrast, has traditionally emphasized disciplinary rigor and technical proficiency [4]. Despite their shared focus on creativity, problem-solving, and innovation, the convergence of these two domains remains underexplored, fragmented, and inconsistently implemented across educational systems [5,6]. Addressing this gap, this study contributes to the growing line of inquiry by offering a multi-dimensional, metadata-driven mapping of how entrepreneurial constructs have been integrated into STEM education over the past two decades.

Previous studies, including systematic reviews of entrepreneurship-oriented pedagogies, innovation skills, and STEM learning, have generated valuable insights into specific subdomains [7–9]. However, these studies typically examine entrepreneurship and STEM education in parallel rather than providing an integrated mapping of their intellectual and conceptual connections. The present study extends this scholarship by employing a combined bibliometric approach, integrating performance analysis, bibliographic coupling, and co-word analysis to capture both the structural foundations and conceptual evolution of this interdisciplinary field.

Several issues drive the urgency of this integration. While technically rigorous, traditional STEM programs often fail to equip students with an entrepreneurial mindset (defined as the cognitive orientations and behavioral dispositions associated with opportunity recognition, creativity, risk tolerance, resilience, and value creation) and capabilities that are necessary for real-world innovation and enterprise development [10,11]. Entrepreneurial learning refers to the experiential, iterative, and reflective processes through which learners develop entrepreneurial competencies by engaging in authentic problem-solving, prototyping, experimentation, and design-based inquiry [12]. Conversely, entrepreneurship education often lacks the scientific and technological foundation that STEM programs provide [13,14]. As a result, graduates may possess technical proficiency without entrepreneurial adaptability or entrepreneurial ambition without sufficient technological depth, limiting their capacity to drive societal transformation [15,16]. This misalignment between theory and application highlights the need for educational paradigms that blend entrepreneurial thinking

with STEM learning environments [17,18].

Beyond curricular design, the problems surrounding this convergence are also rooted in structural and pedagogical limitations. Many institutions struggle to redesign curricula that balance disciplinary rigor with experiential and innovation-oriented learning approaches [19,20]. Faculty readiness, limited interdisciplinary collaboration, and insufficient policy frameworks hinder the embedding of entrepreneurship into STEM disciplines [21,22]. Collectively, these challenges reveal systemic barriers to achieving equitable, sustainable, and innovation-driven education across global contexts.

The literature increasingly highlights the promise of integrating entrepreneurial pedagogies such as problem-based, project-based, and design-thinking approaches into STEM curricula to promote creativity and lifelong learning [2,23]. Studies demonstrate that hands-on, collaborative models such as Fab Labs, makerspaces, and digital learning environments foster students' abilities to ideate, prototype, and commercialize solutions [17,24]. More recently, scholarship has linked entrepreneurship–STEM integration to broader societal objectives, particularly those related to sustainability, inclusivity, and digital transformation [16,25]. However, despite these advancements, a knowledge gap remains in mapping how these themes interact, identifying the conceptual directions that dominate, determining where interdisciplinary collaborations thrive, and understanding how technological innovation influences this evolving intersection [6,13].

The present study advances the understanding of the convergence between entrepreneurship and STEM education by applying bibliometric techniques. By analyzing research patterns, co-authorship networks, and thematic clusters, the study provides an empirical foundation for understanding the intellectual structure of the field and its future directions [26,27]. It offers a structured foundation for STEM educators, researchers, and policymakers seeking to understand emerging trends in pedagogy, technology, and interdisciplinary approaches.

Accordingly, this study is guided by three primary objectives:

1. Analyze research productivity, impact, and publication patterns on the convergence of entrepreneurship and STEM education.
2. Explore the main themes that define current research on the convergence of entrepreneurship and STEM education.
3. Identify emerging topics that can guide future studies on the convergence of entrepreneurship and STEM education.

Overall, this study contributes to shaping an educational paradigm where entrepreneurship and STEM coexist as mutually reinforcing pillars of creativity, employability, and socio-economic progress. By systematically mapping over two decades of scholarship, the study supports evidence-informed curriculum design, research development, and policy planning within STEM education systems.

2. Literature review

The convergence of entrepreneurship and STEM education has gained global traction as education systems aim to prepare students for innovation-driven economies. Recent scholarship emphasizes that fostering entrepreneurial competencies within STEM disciplines enhances creativity, adaptability, and design-thinking skills, which are vital for navigating an uncertain technological future [28,29]. This growing integration represents a paradigm shift away from purely

content-focused instruction and toward experiential, interdisciplinary, and technology-driven pedagogies [30,31].

At the pedagogical level, integrating entrepreneurship into STEM education has redefined traditional learning environments. Studies highlight that project-based, problem-driven, and experiential learning frameworks enable students to apply theoretical knowledge to real-world innovation challenges [31,32]. In addition, maker-based and digital environments, such as Fab Labs and augmented reality learning spaces, foster collaboration, creativity, and applied innovation [19,33]. Similarly, game-based and design-thinking approaches stimulate entrepreneurial mindsets by immersing learners in authentic, iterative problem-solving contexts [14,18]. Across these studies, the convergence of technology and pedagogy is identified as a key mechanism for preparing STEM learners for entrepreneurship and lifelong innovation [34,35]. Within this context, higher education institutions play a pivotal role in cultivating entrepreneurial ecosystems that connect academic research, technological innovation, and enterprise creation. Universities increasingly function as incubators for entrepreneurship through curriculum redesign, interdisciplinary collaboration, and technology transfer mechanisms [36,37].

Beyond pedagogical reform, technological innovation further accelerates the convergence of entrepreneurship and STEM education. Artificial intelligence (AI), 5G, and interactive digital platforms are reshaping entrepreneurship education by enabling adaptive, data-driven, and immersive learning environments [24,38]. These tools facilitate authentic, hands-on learning experiences that mirror industry challenges, thereby enhancing students' design and decision-making abilities [2,39]. More recently, studies have linked such digital transformations with sustainability-oriented goals, highlighting how Industry 4.0 technologies empower STEM learners to develop innovative solutions to societal and environmental challenges [40,41].

Taken together, the literature demonstrates that entrepreneurship and STEM education are no longer separate domains but interconnected components of a broader educational and socio-economic agenda. This convergence supports the development of entrepreneurial ecosystems that integrate pedagogy, technology, and social inclusion, thereby fostering more inclusive, adaptive, and innovation-oriented learning environments. As the field continues to evolve, research increasingly calls for cross-sector collaboration, digital transformation, and global citizenship as guiding principles for 21st-century education. By embedding entrepreneurial thinking within the STEM curricula, educators are positioning learners not merely to adapt to technological change but to lead innovation responsibly and sustainably in an interconnected world.

3. Methodology

This study employs a bibliometric research design to systematically explore and quantify the intellectual, conceptual, and thematic landscape of studies focusing on the convergence of entrepreneurship and STEM education. Bibliometric analysis was chosen for its ability to provide a comprehensive, objective, and replicable overview of a research field by examining publication metadata, including authorship, citations, keywords, and sources. This approach enables the identification of influential contributions, collaboration patterns, and thematic trends that shape academic discourse [27,42]. Figure 1 presents the research framework of the study, which is structured into two main phases: Phase 1, document selection, and Phase 2, bibliometric analysis.

3.1. Phase 1: Document selection

The first phase of this research framework involved the systematic selection of documents to construct a reliable and thematically coherent dataset for bibliometric analysis. The objective was to identify scholarly contributions that represent the evolving intersection of entrepreneurship and STEM education, ensuring methodological rigor and relevance. The process followed established bibliometric protocols emphasizing transparency, replicability, and precision [26,27].

Data were retrieved exclusively from the Scopus database on October 2, 2025. Scopus database was selected as the sole data source due to its broad interdisciplinary coverage, particularly in education, engineering, and social sciences, which are central to the convergence of entrepreneurship and STEM education [43]. Compared to more specialized databases, such as ERIC and the more selective Web of Science Core Collection, Scopus offers broader journal inclusion and more consistent metadata for large-scale bibliometric mapping [44,45]. The reliance on Scopus and English-language publications may underrepresent research produced in non-English-speaking contexts or disseminated through regional outlets [46]. Accordingly, the findings should be interpreted as reflecting dominant international research patterns rather than an exhaustive representation of global scholarship.

Additionally, Scopus is compatible with bibliometric visualization tools, such as VOSviewer [47] and Biblioshiny [26]. The search focused on publications addressing the integration of entrepreneurial concepts in STEM contexts. To refine the dataset, six selection criteria were sequentially applied. First, a Boolean query was applied to the TITLE-ABSTRACT-KEYWORDS fields. The Boolean query provided a structured way to capture publications situated at the intersection of entrepreneurship and STEM education. However, the authors acknowledge that keyword-based retrieval introduces inherent subjectivity. Different studies may conceptualize entrepreneurship and STEM education using alternative terminologies not fully reflected in the search string. The keywords were selected based on the dominant constructs identified in the literature and on accepted terminology in bibliometric studies. Nevertheless, the search strategy does not claim exhaustive coverage of all conceptual framings in the field. The query combined three conceptual dimensions (entrepreneurship, STEM education, and interdisciplinarity), yielding 1,276 initial documents.

Second, the time range (2002–2024) was selected to capture more than two decades of research development, resulting in 1,155 documents. Third, only peer-reviewed articles were retained to ensure academic credibility and consistency, reducing the dataset to 242 documents. Fourth, the dataset was limited to journal publications, excluding nonscholarly sources, resulting in 238 records. Fifth, only English-language publications were included to maintain interpretive uniformity, leaving 224 documents.

Finally, a manual screening process was conducted to verify thematic alignment, eliminate duplicates, and retain only works addressing both entrepreneurship and STEM education. Figure 2 illustrates the PRISMA flow diagram, which shows the rigorous multi-stage screening procedure undertaken to ensure the inclusion of only studies that directly address the convergence of STEM education and entrepreneurship. The manual screening process was conducted by one of the authors, who reviewed titles and abstracts using predefined inclusion and exclusion criteria derived from the research objectives of the study. To reduce subjectivity, a structured screening protocol was applied, including a pilot screening phase to refine criteria and ensure consistent application across records. During this stage, studies that did not address the convergence of entrepreneurship and STEM

education were excluded, including articles that discussed the two domains independently without conceptual integration or those unrelated to educational contexts. Although a single reviewer performed the screening, the use of explicit criteria and iterative verification helped enhance internal consistency and reliability of the final dataset. Ambiguous cases were documented and discussed with the co-authors to maintain conceptual consistency and ensure alignment with the objectives of the study. This multi-stage filtering process resulted in a final dataset of 174 documents, serving as the foundation for the bibliometric analysis phase.

Step 1. Scope of investigation A bibliometric analysis of the convergence of Entrepreneurship and STEM education	
Step 2. Database collection Scopus	
Step 3. Documents selection **First selection criteria:** TITLE-ABSTRACT-KEYWORDS ((STEM OR "STEM education" OR "science education" OR "technology education" OR "engineering education" OR "mathematics education" OR "integrated STEM" OR "STEM learning" OR "STEM teaching" OR "STEM curriculum" OR "STEM training") AND (entrepreneur* OR "entrepreneurship education" OR "entrepreneurial learning" OR "entrepreneurial mindset" OR "enterprise education" OR "enterprise skill*" OR "innovation education" OR "innovation skill*" OR "venture creation" OR "startup education" OR "business creation") AND (integration OR interdisciplin* OR "cross-disciplin*" OR "multi-disciplin*" OR "trans-disciplin*" OR embedded OR incorporat* OR combin* OR "curriculum integration" OR "curriculum design" OR "curriculum development")) **(Resulted in 1276 documents)**	
Second selection criterion: Time interval "prior years up to 2024" **(Resulted in 1155 documents)**	Phase 1: Documents selection
Third selection criterion: Category of documents "Article" **(Resulted in 242 documents)**	
Fourth selection criterion: Source of documents "Journal" **(Resulted in 238 documents)**	
Fifth selection criterion: Language "English" **(Resulted in 224 documents)**	
Sixth selection criterion: Pruning and skimming of documents **(Resulted in 174 documents)**	
Step 4. Processing of selected documents VOSviewer and Biblioshiny	Phase 2: Bibliometric analysis
Step 5. Analysis and inference of results	

Figure 1. Research framework.

The records were exported in comma-separated values (CSV) format using Scopus "Full Record" option, which included the following metadata fields: author information (authors, full names, author IDs, affiliations), document details (title, year, source title, volume, issue, page information, document type, publication stage, language), citation and identifier data (cited-by counts, DOI, PubMed ID, EID, ISSN/ISBN, CODEN), abstract and keyword fields (abstract, author keywords, index keywords), reference lists, and additional metadata (e.g., funding texts, publisher, editors, conference information, open access status, sponsors, and source links). Subsequently, data cleaning and keyword standardization were performed to ensure analytical accuracy and consistency. A custom thesaurus file was developed in VOSviewer and Biblioshiny to consolidate and merge synonymous terms, and a stop list was used to exclude generic and irrelevant terms. This rigorous data preparation process ensured that the dataset was both comprehensive and thematically coherent, reflecting the interdisciplinary nature of the convergence between entrepreneurship and STEM education. The resulting corpus provides a robust empirical basis for subsequent mapping, trend identification, and knowledge structure analysis in Phase 2.
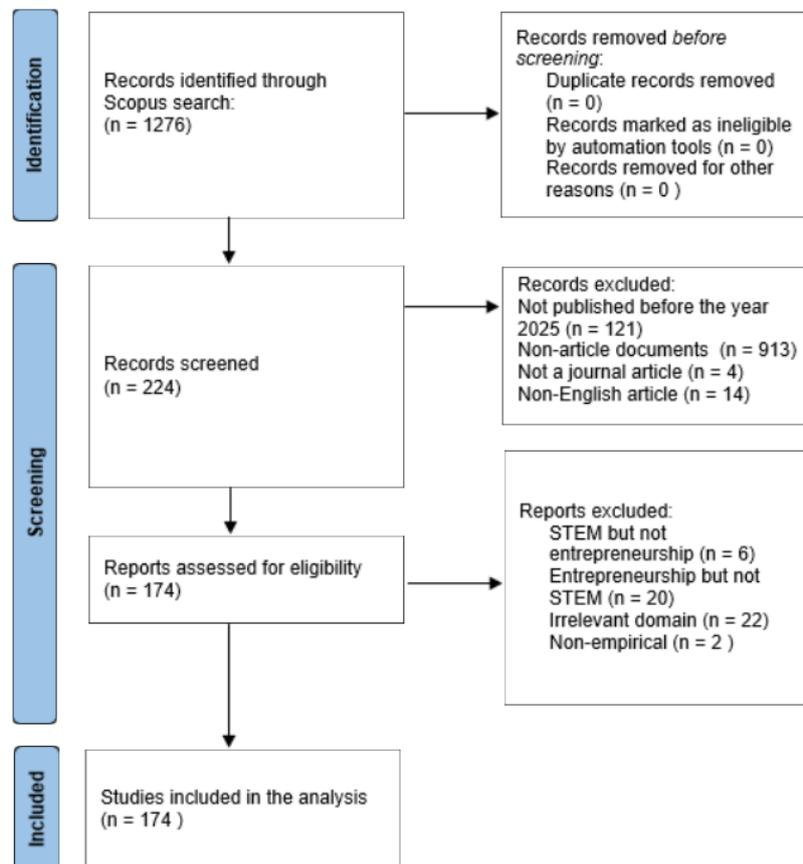
Figure 2. PRISMA flow diagram for screening and eligibility.

3.2. Phase 2: Bibliometric analysis

The second phase of this research framework involved performing a bibliometric analysis that integrated two methodological components (performance analysis and science mapping) to systematically examine the structure, productivity, and intellectual development of research on the convergence of entrepreneurship and STEM education. Bibliometric analysis was chosen because it

enables an objective and quantitative evaluation of the evolution of the field, key contributors, and thematic interconnection, allowing the identification of both mature and emerging research domains [27,48]. This phase employed VOSviewer and Biblioshiny, two complementary tools that facilitate the visualization and interpretation of bibliographic data [26,47].

The performance analysis focused on measuring the research output and scholarly impact of documents related to entrepreneurship and STEM education. Indicators such as publication trends and citation counts, leading publication sources, and influential documents were examined to describe the productivity and dissemination patterns within the field. This analytical focus provides a foundational understanding of the growth of the discipline, identifies prolific contributors, and reveals trajectories of scholarly engagement [49]. By examining publication trends over time, the study established a contextual basis for interpreting the increasing scholarly attention to entrepreneurial integration within STEM education.

The science mapping component comprised bibliographic coupling and co-word analysis, which capture the intellectual and conceptual structures of the research domain. Bibliographic coupling was employed to represent the current research landscape by linking documents with shared references, thereby revealing clusters reflecting common theoretical foundations or methodological approaches [50]. This technique was particularly suited for identifying active research fronts and understanding the intellectual coherence within the field. In line with bibliometric theory, documents sharing a substantial proportion of references are assumed to draw upon similar intellectual bases [50,51]. However, coupling strength alone does not guarantee thematic coherence, as it indicates structural proximity rather than conceptual equivalence. Accordingly, representative documents from each cluster were examined to validate thematic consistency. This combined approach integrates algorithmic results with qualitative interpretation to ensure conceptual validity [42].

Meanwhile, co-word analysis was conducted to explore the future research landscape by examining the co-occurrence among author and index keywords, thereby uncovering emerging topics and thematic relationships [42]. Future research directions and emerging conceptual linkages are identified based on keywords meeting defined minimum occurrence thresholds and exhibiting increasing frequency, connectivity, and temporal prominence [45,52]. Keywords showing stronger presence in later years and greater association with core pedagogical and innovation-oriented terms were interpreted as indicators of developing research directions [53,54]. This procedure enables systematic identification of evolving thematic emphases.

The three bibliometric techniques were combined to form a coherent analytical sequence that supports an integrative understanding of how entrepreneurship and STEM education intersect within contemporary scholarship. Performance analysis establishes the scale and growth of this research domain over time, demonstrating that the integration has evolved into a sustained research domain rather than isolated pedagogical experimentation [42]. Bibliographic coupling reveals the structural organization in current research by identifying clusters of studies that share common intellectual foundations [51]. Co-word analysis traces the conceptual language linking entrepreneurship and STEM education, thereby highlighting emerging thematic emphasis and future directions [52]. Together, these complementary techniques support the interpretation of convergence as both an empirical trend and a conceptual realignment within STEM education research. Consequently, this phase establishes a robust methodological foundation for analyzing trends, influential contributions,

and future research opportunities.

3.3. Cluster stability and validity checks

Several quantitative diagnostics were conducted to assess the stability and validity of the bibliographic coupling and co-word clusters. First, threshold sensitivity tests were performed by varying the minimum reference threshold (2 to 4) for bibliographic coupling analysis and the minimum keyword occurrence threshold (3 to 5) for co-word analysis. Second, agreement between automated cluster descriptors (top-weighted keywords and terms generated by VOSviewer) and inductively assigned thematic labels was examined to evaluate labeling validity. Third, a split-sample cross-validation compared clustering structures between an early period (2002–2014) and a recent period (2015–2024). Detailed diagnostic results are provided in the supplementary material.

3.4. Authors' use of AI tools

In alignment with Committee on Public Ethics (COPE) guidelines on the ethical use of generative AI, the authors clarify that AI tools were used during manuscript preparation. ChatGPT was employed for ideation and conceptual support, outlining assistance, and language refinement. These functions involve refining phrasing, clarifying conceptual structure, and suggesting logical organization. No AI-generated text, data, visualizations, interpretations, or analytical results were incorporated without substantial human revision, verification, and rewriting. Conceptual arguments, methodological decisions, and bibliometric analyses were developed and validated entirely by the authors.

All AI-assisted text underwent manual editing, cross-checking against theoretical and empirical sources, and plagiarism and AI screening using institutional tools to ensure originality and integrity. Analyses were conducted using recognized academic software (VOSviewer, Biblioshiny) and validated by the authors. The final manuscript reflects the intellectual contributions of the authors, analytical reasoning, and academic responsibility.

4. Result and analysis

4.1. Performance analysis

The bibliometric data for this study were retrieved from the Scopus database, providing a comprehensive overview of research publications related to the convergence of entrepreneurship and STEM education. The dataset covers studies published between 2002 and 2024, spanning over two decades of scholarly output in this interdisciplinary field. Across the 174 documents analyzed, a total of 2,559 citations were recorded, resulting in an average of approximately 14.71 citations per publication. The calculated H-index of 26 indicates a moderately strong citation impact, with at least 26 documents receiving 26 or more citations each.
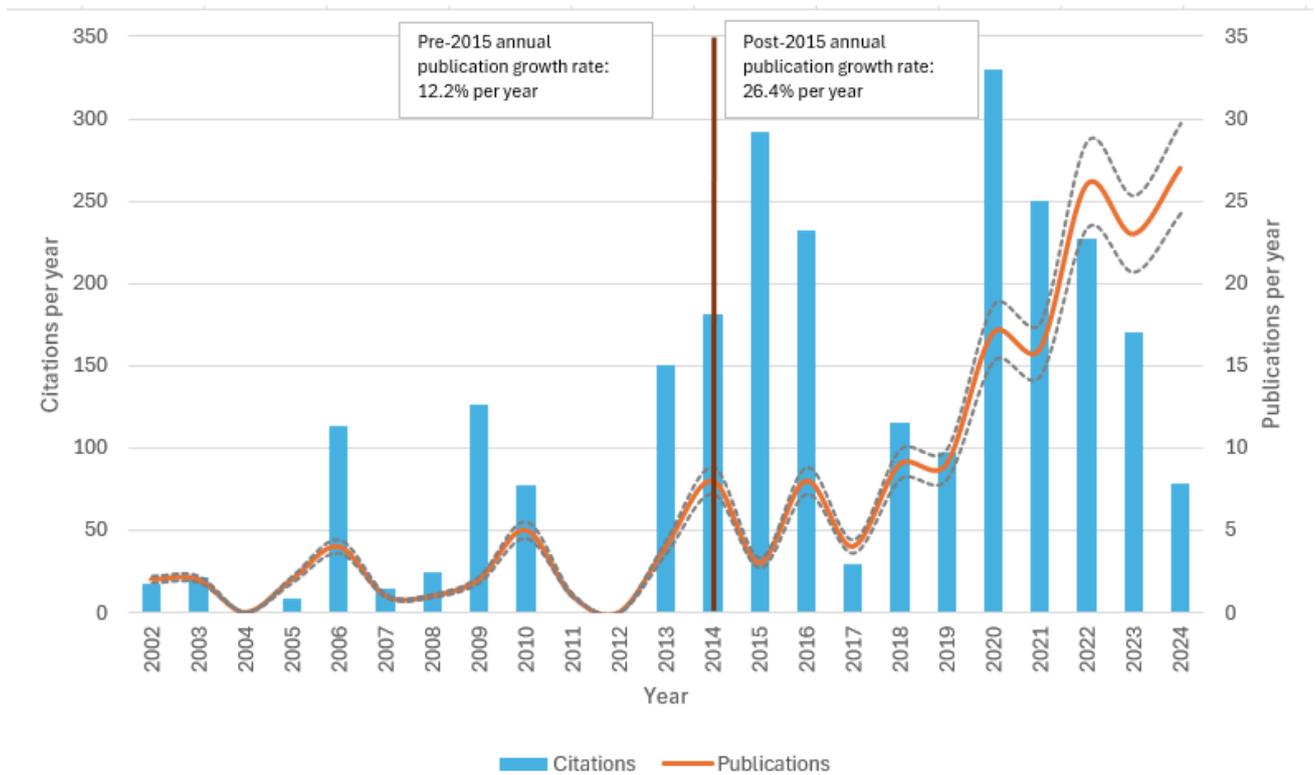
Figure 3. Number of publications and citations on the convergence of entrepreneurship and STEM education.

Figure 3 shows a steady growth in research activity, particularly from 2015 onwards, reflecting an increasing academic focus. The number of publications rose from fewer than 10 annually in the early 2010s to 27 papers in 2024, marking the highest output within the coverage period. This upward trajectory suggests a growing interest in this research domain, which aligns with broader educational reforms emphasizing innovation, creativity, and entrepreneurial competencies in STEM learning environments. The steady rise in citations after 2015, combined with an expanding author base, indicates increasing interdisciplinary engagement across research communities. The data point to a growing interaction across domains, moving from isolated studies toward a more cohesive body of knowledge connecting innovation, education, and enterprise development.

However, growth in publication volume alone should not be interpreted as definitive evidence of field maturity. Bibliometric output reflects scholarly activity but does not inherently indicate theoretical consolidation, methodological rigor, or conceptual coherence. Accordingly, the trends observed illustrate increasing scholarly attention to entrepreneurship–STEM integration within Scopus-indexed literature rather than a comprehensive assessment of the intellectual maturity of the field.

Table 1 presents the top 10 most cited documents that form the core knowledge base shaping the convergence of entrepreneurship and STEM education. The most influential work is that of Bevan et al. [17], which has garnered 257 citations, bridging entrepreneurship with STEM learning through experiential and leadership-oriented approaches. This was followed by studies from Farr and Brazil [55], which garnered 121 citations, and Duval-Couetil et al. [13], with 112 citations, both of

which extend the convergence toward inclusivity, sustainability, and innovation-related competencies.

Table 1. Top 10 highest cited documents.

No	Title	Author(s)	Citation
1	Learning Through STEM-Rich Tinkering: Findings From a Jointly Negotiated Research Project Taken Up in Practice.	Bevan, B., Gutwill, J. P., Petrich, M., & Wilkinson, K. (2015).	257
2	Leadership Skills Development for Engineers.	Farr, J. v., & Brazil, D. M. (2009).	121
3	Examining the minimal combined effects of gender and minoritized racial/ethnic identity among academic entrepreneurs.	Duval-Couetil, N., Epstein, A., & Huang-Saad, A. (2024).	112
4	The importance of surrogate entrepreneurship for incubated Swedish technology ventures.	Lundqvist, M. A. (2014).	104
5	An integrated project of entrepreneurship and innovation in engineering education.	Soares, F. O., Sepúlveda, M. J., Monteiro, S., Lima, R. M., & Dinis-Carvalho, J. (2013).	76
6	Fostering skills for the 21st century: The role of Fab labs and makerspaces.	Rayna, T., & Striukova, L. (2021).	67
7	Reconsidering the Regional Economic Development Impacts of Higher Education Institutions in the United States.	Drucker, J. (2016).	63
8	Science-based entrepreneurship education as a means for university-industry technology transfer.	Blankesteijn, M., Bossink, B., & van der Sijde, P. (2021).	53
9	The Sustainable Development Goals (SDGs) as a Basis for Innovation Skills for Engineers in the Industry 4.0 Context.	Rivera, F. M. la, Hermosilla, P., Delgadillo, J., & Echeverría, D. (2020).	48
10	An entrepreneurship education taxonomy based on authenticity. European Journal of Engineering Education.	Aadland, T., & Aaboen, L. (2020).	47

Table 2 presents the top 12 sources, ranked by the number of documents and their corresponding citations. The *International Journal of Engineering Education* leads with 17 publications and 151 citations, highlighting engineering education as the primary platform for integrating entrepreneurial learning. *Advances in Engineering Education* ranks first in terms of citations (201), indicating its significant influence on pedagogical innovation. Other key contributors, including the *European Journal of Engineering Education* and the *Applied Mathematics and Nonlinear Sciences*, highlight the blend of technical and entrepreneurial perspectives of the field. Collectively, these journals demonstrate a growing scholarly commitment to embedding entrepreneurship within STEM-focused educational contexts.

Table 2. Top 12 sources based on documents and their citations.

No	Source	Documents	Citation
1	International Journal of Engineering Education	17	151
2	Advances in Engineering Education	13	201
3	European Journal of Engineering Education	8	99
4	Applied Mathematics and Nonlinear Sciences	5	2
5	Education Sciences	4	70
6	Journal of Technology Transfer	3	48
7	International Journal of Technology and Design Education	3	42
8	International Journal of Engineering Pedagogy	3	35
9	Eurasia Journal of Mathematics, Science and Technology Education	3	22
10	Frontiers in Education	3	10
11	World Transactions on Engineering and Technology Education	3	7
12	Journal of Engineering Education Transformations	3	2

The performance analysis focused on publication volume, citation impact, and source productivity to characterize the growth trajectory and scholarly influence of research on entrepreneurship and STEM education. While regional and institutional analyses can provide additional insight into geographic concentration and organizational leadership, such analyses fall beyond the scope of the present study, which emphasizes thematic and intellectual structure rather than comparative benchmarking. Taken together, the indicators employed establish the temporal expansion, citation visibility, and disciplinary anchoring of the field, providing a foundation for subsequent structural and conceptual analyses.

4.2. Bibliographic coupling analysis

Bibliographic coupling and co-word analysis both generate clustered structures, but they capture different dimensions of the research field. The alignment between the two sets of clusters is interpretive rather than structural, and differences between them are therefore expected. Bibliographic coupling identifies the intellectual structure of the literature by grouping studies that share common reference bases, reflecting shared theoretical or methodological foundations. In contrast, co-word analysis maps the conceptual structure of the field through patterns of keyword co-occurrence, highlighting dominant and emerging themes. These techniques offer a complementary perspective on how knowledge is organized and how research themes evolve within the convergence of entrepreneurship and STEM education.

From the initial dataset of 174 documents retrieved from the database, using a full-counting method with association strength normalization, 137 documents met the threshold criterion of having at least two cited references. Sixty-two documents representing the most interconnected publications were retained for analysis. Multiple threshold values were tested to ensure the formation of robust and well-balanced clusters, ultimately selecting a value that avoids overly simplistic or excessively complex visualizations. A minimum of eight documents per cluster was set to ensure adequate thematic grouping. The final threshold provided the optimal clarity and thematic coherence of the bibliographic coupling network.

The analysis revealed that the four most strongly coupled publications were Kim and Strimel [10] with 26 citations and a total link strength of 14 and Rakicevic et al. [6] with 11 citations and a total link strength of 11. These were followed by Bosman and Shirey [18] with 3 citations and Adland and Aaboen [56], with 47 citations, both of which had a total link strength of 9. Table 3 presents the 10 most bibliographically coupled documents and their total link strength, indicating the cumulative strength of a publication's connection to other documents [52].

Based on network visualization, bibliographic coupling analysis produced four distinct clusters. Figure 4 shows the network structure of bibliographic coupling analysis. Each cluster was labeled and characterized based on representative publications, following the authors' inductive interpretation of the four clusters. The clusters reflect publications with similar referencing patterns, which may suggest shared thematic orientations. To avoid overinterpretation of the network structure, thematic labels were assigned only after examining the titles and abstracts of key documents within each cluster, ensuring that interpretations were grounded in substantive content rather than solely in visual proximity.

Cluster 1 (red): This cluster is labeled "Socio-technical pedagogies for sustainable and inclusive entrepreneurial STEM learning." This cluster highlights studies that emphasize authentic pedagogies, including socioscientific inquiry, engineering challenges, and STEM-rich tinkering, which foster creativity, autonomy, and problem-solving [17,28,29]. A secondary thematic emphasis relates to sustainability and Industry 4.0 ecosystems. Studies indicate that the sustainable development goals (SDGs) and emerging technological competencies increasingly shape entrepreneurial skill formation, encouraging environmentally and socially responsible innovation [9,16,25,57]. The cluster also foregrounds inclusivity and institutional support, with research examining gendered participation in STEM entrepreneurship [58,59] and learning gains associated with structural reforms in educational settings [60,61].

Table 3. Top 10 documents with the highest bibliographic coupling.

No	Document	Citation	Total link strength
1	Kim, E., & Strimel, G. J. (2020). The Influence of Entrepreneurial Mindsets on Student Design Problem Framing. *IEEE Transactions on Education*, *63*(2), 126–135.	26	14
2	Rakicevic, Z., Rakicevic, J., Labrovic, J. A., & Ljamic-Ivanovic, B. (2022). How Entrepreneurial Education and Environment Affect Entrepreneurial Readiness of STEM and Business Students? A Longitudinal Study. *Engineering Economics* , *33*(4), 414–432.	11	11
3	Bosman, L., & Shirey, K. L. (2023). Using STEAM and Bio-Inspired Design to Teach the Entrepreneurial Mindset to Engineers. *Open Education Studies*, *5*(1).	3	9
4	Aadland, T., & Aaboen, L. (2020). An entrepreneurship education taxonomy based on authenticity. *European Journal of Engineering Education*, *45*(5), 711–728.	47	9
5	Barth, J., & Muehlfeld, K. (2022). Thinking out of the box—by thinking in other boxes: a systematic review of interventions in early entrepreneurship vs. STEM education research. *Management Review Quarterly*, *72*(2), 347–383.	14	8
6	Eltanahy, M., & Mansour, N. (2022). Promoting UAE entrepreneurs using E-STEM model. *The Journal of Educational Research*, *115*(5), 273–284.	5	8
7	Wasim, J., Haj Youssef, M., Christodoulou, I., & Reinhardt, R. (2024). Higher education	16	7

	student intentions behind becoming an entrepreneur. *Higher Education, Skills and Work-Based Learning*, *14*(1), 162–180.		
8	Earle, A. G., Merenda, M. J., Short, K. M., Thein, M.-W. L., & Sedam, M. C. (n.d.). *Advances in Engineering Education Lean Collaboration on Campus? A Social Network and Bricolage Approach.*	2	7
9	Eltanahy, M., Forawi, S., & Mansour, N. (2020). Incorporating Entrepreneurial Practices into STEM Education: Development of Interdisciplinary E-STEM Model in High School in the United Arab Emirates. *Thinking Skills and Creativity*, *37*, 100697.	40	6
10	Mehta, K., Entrepreneurship, S., Brannon, M. L., & Zhao, Y. U. (2016). An Educational and Entrepreneurial Ecosystem to Actualize Technology-Based Social Ventures. *Advances in Engineering Education*, *5*(1)	24	6

Cluster 2 (green): This cluster is labeled "Curriculum integration and experiential pedagogies for entrepreneurial mindset development in STEM education." Studies in this cluster emphasize authentic engagement in real or simulated innovation processes, with authenticity identified as a core dimension of entrepreneurship education [56]. Intensive, challenge-based programs demonstrate how time-bound design experiences foster ideation, resilience, and ownership of problem-solving processes [62,63]. Design thinking, bio-inspired design, and team-based projects enhance entrepreneurial mindsets by strengthening students' problem-framing skills [10,18,64]. Complementary support structures, such as ICT-enabled entrepreneurial platforms [65], micro-credentialing pathways [66], and experiential learning models [67], scaffold the development of these competencies. Curricular transformation efforts, including the integration of innovation in engineering programs [68], CDIO frameworks [69], and course-competition models [70], further institutionalize experiential entrepreneurship learning within STEM curricula.

Figure 4. Bibliographic coupling analysis of the convergence of entrepreneurship and STEM education.

Cluster 3 (blue): This cluster is labeled "Pedagogical design frameworks for competency-oriented entrepreneurial STEM education." Studies in this cluster focus on the pedagogical frameworks and teacher competencies required to integrate entrepreneurship effectively within STEM education. Central to this cluster are interdisciplinary E-STEM models that embed entrepreneurial practices within STEM instruction [71,72]. A growing emphasis on teacher readiness highlights the need for educators to reconcile scientific, social, and economic dimensions of learning [73,74]. Accordingly, professional development emerges as a critical factor in strengthening teachers' self-efficacy for designing lessons that integrate computational thinking, problem-solving, and entrepreneurial skills [75,76]. Project-based learning and tools such as Arduino support the development of the 4Cs (critical thinking, creativity, collaboration, and communication), thereby enhancing entrepreneurial intentions and workforce readiness [77–79].

Cluster 4 (yellow): This cluster is labeled "Institutional and industry mechanisms shaping entrepreneurial readiness in STEM education." This cluster examines the institutional and contextual factors shaping the transition from STEM education to entrepreneurial activity, particularly among engineering graduates. It highlights the cultivation of the engineering entrepreneurial mindset (EEM) through structured socio-technical design challenges embedded in early curricula, which promote curiosity and value creation through hands-on learning [80,81]. The higher education–industry interface emerges as a key determinant of entrepreneurial readiness, with industry–teaching integration models, intelligent manufacturing platforms, and vocational training systems strengthening innovation capacity [2,82]. Students' engagement in surrogate entrepreneurship and co-pilot roles within technology transfer further supports venture learning [15,37]. The cluster also highlights contextual and inclusion-related factors influencing readiness across student groups, including gender-specific challenges [6,83].

4.3. Co-word analysis

For the co-word analysis, a thesaurus file was applied to standardize keyword variants and merge synonymous terms. A total of 874 author and index keywords were retrieved, and full counting with association strength normalization was used to determine their co-occurrence relationships. Several minimum-occurrence thresholds were tested to identify a configuration that produced interpretable and analytically meaningful clusters. The final threshold was set at a minimum of four occurrences, resulting in 48 keywords and generating a co-word network with sufficient density for thematic interpretation, while avoiding overly fragmented or overly generalized structures. A minimum cluster size of eight documents was maintained to ensure thematic stability in the resulting map.

The co-occurrence analysis shows that "engineering education" has the highest prominence, with 108 occurrences and a total link strength of 520, indicating its central role in the research network. This was followed by "students" (61 occurrences; total link strength = 359) and "curricula" (52 occurrences; total link strength = 279), reflecting strong interconnections with teaching and learning themes. Keywords, such as "entrepreneurship" (52 occurrences; total link strength = 213) and "innovation skills" (31 occurrences; total link strength = 175), further link educational practice with innovation-oriented outcomes. Together, these patterns indicate that engineering-focused pedagogical contexts constitute the core structural backbone through which entrepreneurial concepts are integrated. Table 4 summarizes the top 15 co-occurring keywords, their number of occurrences, and total link strength.

Table 4. Top 15 keywords in the co-occurrence of keywords analysis.

No	Keyword	Occurrences	Total link strength
1	engineering education	108	520
2	students	61	359
3	curricula	52	279
4	entrepreneurship	52	213
5	innovation skills	31	175
6	pedagogy	31	165
7	entrepreneurship education	33	160
8	education	25	138
9	technology-enhanced learning	21	123
10	higher education	25	119
11	project-based learning	20	110
12	multidisciplinarity	16	104
13	design thinking	17	95
14	professional aspects	12	78
15	experiential learning	11	70

Figure 5 presents the cumulative keyword occurrences, which reveal a steady and accelerating growth in research since 2015. A sharp increase has been evident in "engineering education," "students," and "entrepreneurship," indicating their emergence as dominant thematic anchors. The rising prominence of "curricula," "teaching," and "project-based learning" reflects a growing pedagogical shift toward experiential and learner-centered instructional models. Meanwhile, "innovation" and "entrepreneurship education" exhibit sustained growth, suggesting strengthened interdisciplinary integration. More recently, the emergence of "artificial intelligence" and "education computing" after 2020 signals the digital transformation of STEM education, highlighting an increasingly close alignment between technology, entrepreneurial practice, and educational innovation.

Figure 6 presents the network map of the co-word analysis. The map produced four clusters, which were classified and labeled based on the authors' inductive interpretation of keyword co-occurrence patterns.

Cluster 1 (red): With 15 keywords, this cluster is labeled "Technology-enhanced active learning systems in STEM entrepreneurship." This cluster highlights technology-enhanced learning environments that integrate active, collaborative, problem-based, and project-based learning approaches, positioning students as designers and decision-makers in STEM entrepreneurship. Within engineering education, these pedagogies foster entrepreneurial mindsets through experimentation, teamwork, and authentic problem-solving experiences [81,84]. Emerging technologies, including virtual reality, computer-aided instruction, and e-learning systems, extend learning environments by enabling immersive simulations and flexible innovation spaces [85,86]. In addition, the integration of AI and learning analytics strengthens learning systems by supporting adaptive feedback and personalized learning pathways [31,38]. Collectively, these technology-enhanced approaches transform STEM classrooms into dynamic ecosystems where creativity, opportunity recognition, and innovation behaviors are systematically cultivated [87,88].

Cluster 2 (green): With 12 keywords, this cluster is labeled "Curriculum-integrated innovative pedagogies for experiential STEM entrepreneurship." This cluster reflects a shift from content-driven instruction toward experiential learning grounded in design thinking, product design, and hands-on activities within makerspaces and Fab Labs, where students iteratively explore, test, and refine solutions [19,89]. Such approaches represent innovative pedagogical models embedded within the STEM entrepreneurship curricula, and closely mirror real-world innovation processes [2]. Multidisciplinarity further strengthens this ecosystem by integrating engineering, business, and social perspectives, thereby enhancing opportunity recognition and team-based innovation [32,90]. Equally important, institutional mechanisms, particularly technology transfer and university-industry collaboration structures, connect academic innovation with real-world application [13,36]. Curriculum-integrated innovation ecosystems cultivate entrepreneurial capability through experiential design and institutional linkages [31].

Cluster 3 (blue): With 11 keywords, this cluster is labeled "Entrepreneurial competencies for employability in Industry 4.0-driven STEM education." This cluster highlights the role of education in cultivating entrepreneurial and innovative competencies that drive employability in rapidly evolving technological contexts. Higher education, particularly engineering education, functions as a central site for intentional development of these competencies through adaptive pedagogical strategies. A defining influence within this cluster is Industry 4.0, which reshapes curricula and workforce expectations by prioritizing adaptability, problem-solving, and opportunity recognition skills [40,41]. The presence of an entrepreneurial ecosystem highlights the importance of partnerships and innovation networks linking universities and industry [91,92]. Moreover, the integration of sustainability reflects a shift toward socially responsible innovation, emphasizing the need for graduates equipped to address complex environmental and societal challenges.

Cluster 4 (yellow): With 10 keywords, this cluster is labeled "Inclusive human capital entrepreneurial mindset development in STEM professional formation." This cluster highlights the human, social, and professional dimensions of entrepreneurship within STEM education. It emphasizes how engineers develop entrepreneurial mindsets through entrepreneurship education, institutional practices, and workforce-oriented pathways [39,75]. Central to this cluster is the alignment of entrepreneurial development with leadership, innovation capability, and career progression, positioning entrepreneurship as a core professional competence rather than solely venture creation [36,78]. The inclusion of human resource management perspectives underscores the role of organizational practices in shaping entrepreneurial behavior, while the emphasis on inclusion and diversity highlights equitable access to entrepreneurial opportunities [11,59]. Overall, this cluster reflects a shift toward human-centered, inclusive models of entrepreneurial development embedded within STEM education systems.

The thematic patterns identified through co-word analysis align with recent extensions of the technology acceptance model (TAM) and self-determination theory (SDT), which emphasize self-efficacy, emotional engagement, and institutional support as key mechanisms shaping learners' adoption of technology-rich educational environments. Empirical evidence suggests that self-efficacy and playfulness positively influence perceived usefulness and ease of use, while emotional engagement and university support moderate the adoption of AI-driven and hybrid learning tools [93]. These mechanisms closely correspond to the readiness, intention, and competency constructs identified in the clusters, suggesting that entrepreneurship–STEM curricula gain stronger traction when they foster confidence, reduce technology-related anxiety, and provide institutional

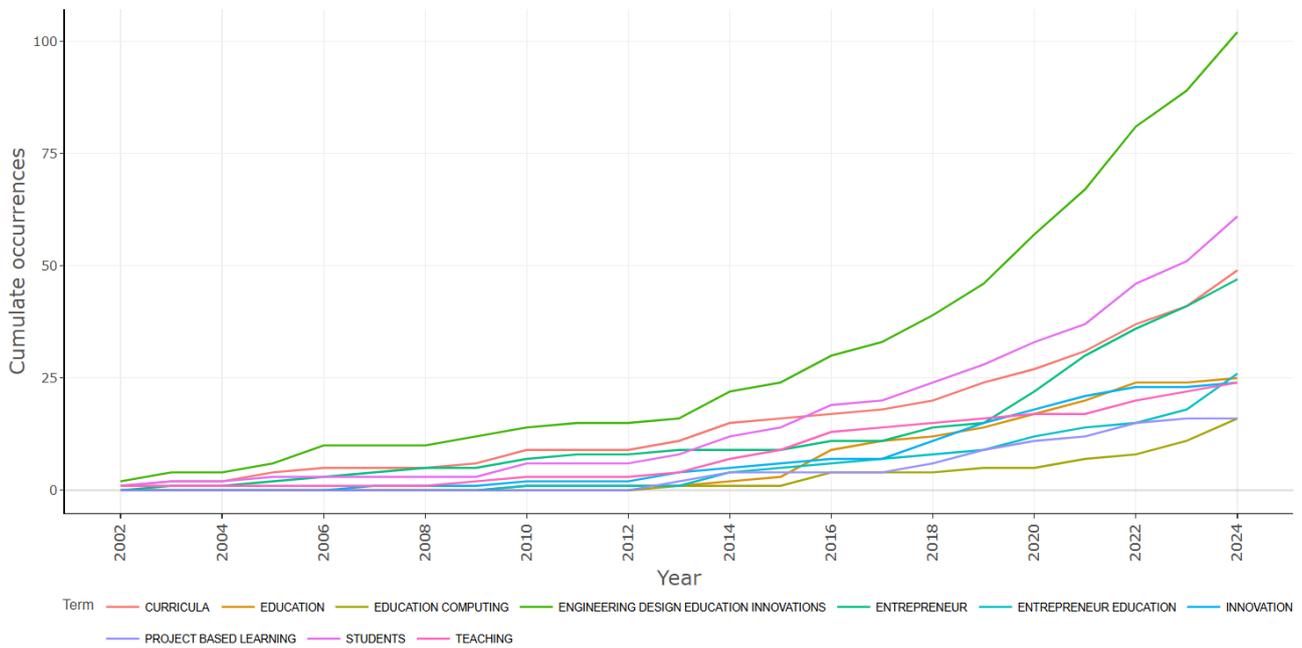scaffolding that supports autonomy and sustained engagement.

Figure 5. Cumulative occurrences of keywords on the convergence of entrepreneurship and STEM education.
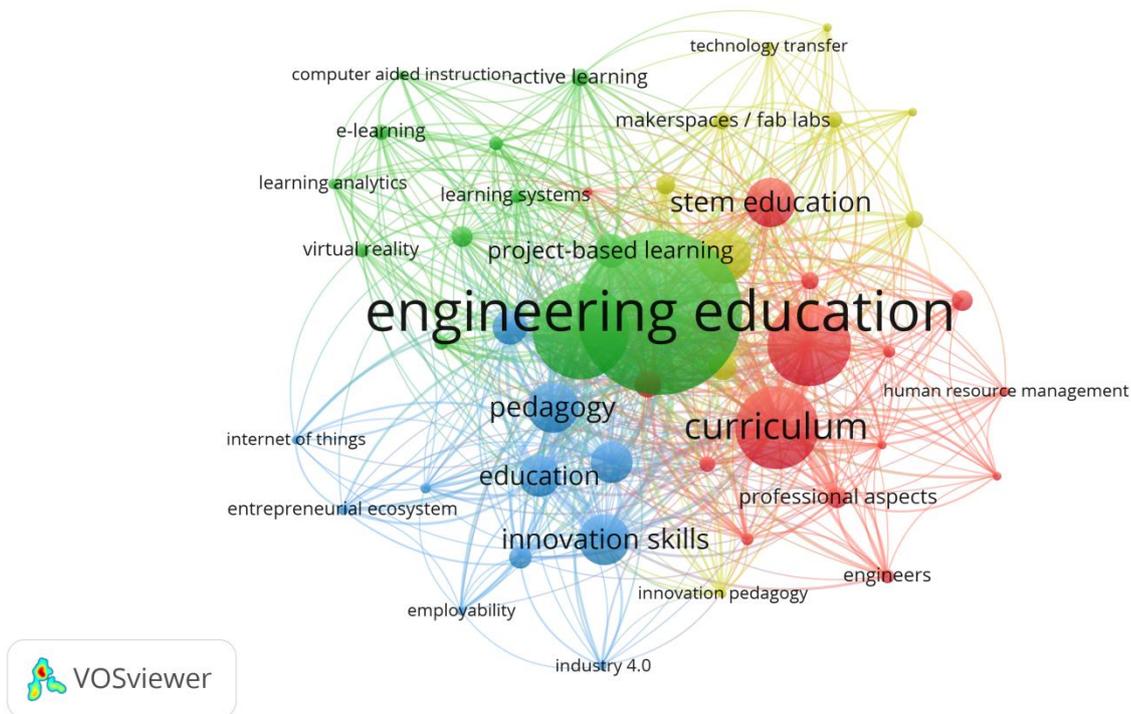

Figure 6. Co-word analysis of the convergence of entrepreneurship and STEM education.

5. Discussion

The bibliometric analysis of the convergence of entrepreneurship and STEM education presents an evolving and increasingly cohesive body of scholarship that bridges innovation, pedagogy, and technological advancement. The findings from the performance, bibliographic coupling, and co-word analysis collectively reveal the intellectual growth, thematic focus, and emerging trajectories of this interdisciplinary domain.

Taken together, the findings address the longstanding divide between technically rigorous STEM education and entrepreneurship education, which often lacks technological depth. Performance analysis demonstrates that this divide has become an increasingly focal concern of global scholarship since 2015. Bibliographic coupling analysis reveals that contemporary research no longer treats entrepreneurship and STEM as parallel domains, but increasingly conceptualizes them as interdependent systems connected through experiential pedagogy, institutional mechanisms, and innovation ecosystems. Co-word analysis further confirms this integration at the conceptual level, where engineering education, entrepreneurship education, innovation skills, and technology-enhanced learning converge within a shared thematic space. Together, these results form a coherent analytical sequence, in which the research problem, methodological design, and empirical evidence align to demonstrate that the entrepreneurship–STEM divide is being addressed through integrative, interdisciplinary, and technology-mediated educational models.

The performance analysis highlights steady and sustained research growth since 2015, indicating rising recognition of the importance of embedding entrepreneurial competencies within STEM education. The field's expanding publication output and citation impact reflect increasing scholarly engagement, supported by educational reform and innovation-driven policies. Key publications, such as those by Bevan et al. [17] and Farr and Brazil [55], have provided influential frameworks linking entrepreneurial practice with creativity and hands-on STEM learning. Similarly, the most active publication outlets, including the *International Journal of Engineering Education* and *Advances in Engineering Education*, underscore the field's emphasis on engineering pedagogy as a foundation for cultivating innovation and entrepreneurial mindsets. Collectively, this performance landscape reflects a gradual shift from traditional, content-driven instruction toward experiential and skill-oriented learning models that better equip students to navigate complex technological and economic challenges.

The formation of distinct yet complementary clusters reflects the multifaceted evolution of research at the intersection of entrepreneurship and STEM education. These clusters have emerged in response to diverse epistemic entry points into the field, including pedagogical design traditions, institutional and policy-driven innovation agendas, and workforce-oriented competency frameworks. As STEM education increasingly engages with entrepreneurial objectives, researchers have approached this convergence through disciplinary perspectives shaped by engineering education, learning sciences, innovation studies, and policy discourse. Accordingly, the resulting clusters represent not isolated research streams but differentiated responses to shared educational and societal challenges, including innovation capacity building, sustainability imperatives, and digital transformation.

The bibliographic coupling analysis reveals four distinct intellectual clusters that define the current research landscape. These clusters collectively portray the field as moving toward integrative, experiential, and sustainability-oriented education models. At the same time, the broader literature

also reflects tensions and inconsistencies that warrant careful consideration. Studies within the same cluster frequently differ in their conceptualization of entrepreneurial competence, the role of technology, and the intended purpose of integrating entrepreneurship into STEM curricula. Some contributions emphasize innovation-driven economic outcomes, whereas others prioritize equity, sustainability, or pedagogical reform. These divergent orientations indicate that entrepreneurship–STEM integration is not a fully unified domain, but rather a heterogeneous and evolving field characterized by multiple, sometimes competing, perspectives.

The observed heterogeneity within and across clusters reflects underlying disciplinary, institutional, and contextual differences shaping research priorities. Studies grounded in engineering and technology education often emphasize problem-solving, design thinking, and technical innovation [18,64], whereas research informed by business and entrepreneurship education foregrounds opportunity recognition, value creation, and venture orientation [32,87]. In addition, regional policy environments and national innovation agendas influence how entrepreneurship is positioned within STEM curricula, with some contexts prioritizing workforce readiness and others emphasizing sustainability or social innovation [77,79,94]. Importantly, this heterogeneity does not undermine the coherence of the field; rather, it highlights the adaptive and context-sensitive nature of entrepreneurial STEM education and cautions against one-size-fits-all interpretations of competence development.

Cluster 1 highlights socio-technical and sustainability-oriented approaches, where authentic design experiences, Industry 4.0 competencies, and inclusive learning environments cultivate creativity, autonomy, and socially responsible innovation [16,28,58]. Cluster 2 builds on this foundation by emphasizing curriculum integration and experiential pedagogies, such as design thinking, makerspaces, and challenge-driven activities, which embed entrepreneurial mindset development directly within engineering education. These approaches are supported by ICT platforms, micro-credentials initiatives, and curricular reforms [18,56,68]. Cluster 3 extends the discussion toward the competencies of teachers and instructors, positioning educators as central agents in operationalizing E-STEM models and designing learning experiences that integrate scientific inquiry with entrepreneurial thinking. Professional development initiatives and STEM project-based pedagogies enhance teacher self-efficacy and promote students' acquisition of the 4Cs and entrepreneurial intentions [71,75,78]. Cluster 4 highlights institutional mechanisms, socio-technical experiences, and contextual factors that shape entrepreneurial readiness. University–industry integration, technology transfer practices, surrogate entrepreneurship, and demographic play a significant role in shaping learners' transition from engineering education to entrepreneurial action [6,37,83]. Collectively, these clusters reveal the evolution of research from localized program evaluations toward broader discourses on innovation ecosystems, educational equity, and industry relevance.

The steady increase in keyword occurrences after 2015 indicates growing research momentum within the field. Co-word analysis further illustrates the conceptual structure and future research directions of entrepreneurship–STEM scholarship. Keywords such as "engineering education," "students," "curricula," and "entrepreneurship" dominate, reflecting a strong pedagogical focus on curriculum innovation and experiential learning. The prominence of innovation and project-based learning suggests that creativity, design thinking, and real-world application have become central learning outcomes in entrepreneurial STEM contexts. More recently, emerging terms, such as

"artificial intelligence," "education computing," and "virtual reality," highlight the digital transformation of entrepreneurship education, signaling the integration of immersive and intelligent technologies into STEM learning ecosystems.

The inclusion of "artificial intelligence" among the top co-occurring keywords highlights the growing integration of AI-mediated tools in entrepreneurship and STEM pedagogy. Recent evidence suggests that students' prior experience with AI moderates the relationship between usability and active learning, indicating that familiarity, rather than novelty, drives effective engagement [95]. AI-enabled tools, such as intelligent assistants and adaptive feedback systems, appear to be most effective when they extend established learning routines and support iterative problem-solving and opportunity recognition. These findings highlight the need to build learners' AI literacy to maximize pedagogical benefits within entrepreneurship and STEM contexts. Results also indicate that organizational support, technological competence, and policy frameworks jointly shape how emerging technologies foster innovative learner behavior. Studies conducted in AI-enabled educational settings demonstrate that clear institutional strategies, structured training, and supportive policies enhance creativity and performance, underscoring the enabling role of institutions and policymakers in entrepreneurship-oriented STEM ecosystems [96].

Rather than functioning as independent domains, the identified clusters interact through shared pedagogical logics and institutional linkages. Socio-technical and sustainability-oriented pedagogies provide normative and contextual foundations that inform curriculum-integrated experiential models, while institutional and industry-linked mechanisms translate these pedagogical approaches into pathways for entrepreneurial readiness and venture engagement. Co-word analysis further indicates conceptual overlap across clusters through recurring themes such as innovation skills, technology-enabled learning, and entrepreneurial mindset development. Taken together, these interaction mechanisms suggest that convergence within this field occurs through cumulative alignment across pedagogical design, curricular implementation, and institutional ecosystems, rather than through linear or sequential progression.

Collectively, the three analyses reveal a dynamic research landscape that has progressed from examining the pedagogical feasibility of integrating entrepreneurship into STEM toward advancing more systemic models of innovation and sustainability. The convergence of entrepreneurship and STEM education is increasingly characterized by interdisciplinary collaboration, digital transformation, and a focus on social responsibility. This evolution reflects a broader educational shift toward preparing learners not only as technically competent professionals but also as innovative problem-solvers and responsible entrepreneurs capable of addressing complex societal and environmental challenges. The bibliometric evidence positions this field as a critical nexus for fostering creativity, employability, and sustainable innovation in 21st-century education.

6. Conclusions

This study establishes a foundational understanding of how entrepreneurship and STEM education converge as complementary drivers of innovation, creativity, and sustainability. Through bibliometric analysis, it highlights a growing shift from discipline-specific instruction toward more integrated, experiential, and socially responsible learning ecosystems. The findings reveal an emerging consensus that entrepreneurship enhances STEM education by fostering adaptability, innovation, competence, and ethical awareness. Accordingly, the study underscores the importance

of cultivating learners who are not only technologically adept but also capable of transforming ideas into meaningful societal solutions. By bridging theory, technology, and practice, the integration of entrepreneurship and STEM education emerges as a cornerstone for building equitable, future-ready, and innovation-driven societies.

7. Implications

The convergence of entrepreneurship and STEM education signifies a transformative shift in preparing learners for innovation-driven, technology-intensive futures. Findings from this bibliometric analysis reveal both theoretical and practical insights that deepen understanding of how education systems can foster creativity, problem-solving, and sustainability. By mapping research trends and thematic clusters, the study establishes an evidence-based framework for integrating entrepreneurial competencies within STEM disciplines.

From a theoretical perspective, this study advances the conceptual foundation of entrepreneurship-STEM integration by framing it as a multi-dimensional learning paradigm that bridges innovation, education, and socio-economic development. It extends existing theories of human capital and innovation diffusion by demonstrating how entrepreneurship enhances STEM education through experiential, technology-supported, and sustainability-oriented approaches. The emergence of themes such as digital transformation, interdisciplinary collaboration, and ethical innovation suggests an evolving theoretical model in which students are positioned as co-creators of knowledge, equipped with both technical expertise and entrepreneurial vision.

From a practical perspective, the study highlights targeted opportunities to strengthen entrepreneurial and innovation skills across educational levels. In K–12, simplified design-thinking activities and introductory entrepreneurial mindset modules can support early development of creativity, confidence, and opportunity recognition. In undergraduate STEM programs, structured experiential learning, such as design-thinking tasks, venture canvases, makerspace-based assessment rubrics, and interdisciplinary micro-credentials, incorporating AI tools and sustainability challenges can develop opportunity-related skills aligned with dominant innovation clusters. For graduate and professional learners, innovation studios that integrate AI-supported research, sustainability-oriented projects, and industry mentorship can enhance responsible innovation capacity. At the system level, policy and strategic planning modules are essential for building institutional readiness and fostering technology-rich entrepreneurial ecosystems.

These strategies collectively promote entrepreneurial mindsets and real-world problem-solving among STEM learners. Institutions are encouraged to establish innovation hubs and partnerships that connect academia, industry, and community development. Policymakers may leverage these insights to design inclusive frameworks that promote sustainability and equitable participation. These implications position the convergence of entrepreneurship and STEM as a foundation for cultivating adaptable, future-ready, and socially responsible graduates.

8. Limitations and future works

While this study provides a comprehensive overview of the convergence between entrepreneurship and STEM education, several limitations should be acknowledged. First, the analysis relied exclusively on the Scopus database, which, despite its breadth, may exclude relevant

studies indexed in other databases such as Web of Science or ERIC. This reliance may have contributed to the underrepresentation of non-English and region-specific publications, particularly from developing regions where entrepreneurial-STEM integration is emerging. Consequently, the intellectual landscape identified in this study may reflect journals with higher international visibility and English-language dominance, potentially narrowing the thematic diversity observed in the clusters.

Second, although bibliometric methods are effective for mapping large-scale research patterns, they do not capture the qualitative nuances of pedagogical innovation, institutional culture, or learner experience. Since bibliometric analyses rely exclusively on metadata, the present study cannot assess the depth, quality, or theoretical sophistication of individual contributions. This limitation may result in greater emphasis on publication volume or citation visibility rather than on substantive conceptual advancement.

Third, the interpretation of network structures depends on algorithmic clustering procedures, which may simplify or obscure complex intellectual relationships. As a result, the findings reflect structural patterns within the Scopus-indexed corpus rather than definitive or comprehensive statements about the field as a whole, and should therefore be interpreted as exploratory. Fourth, the temporal range of the dataset (2002–2024) captures the evolution of the field up to recent years. However, rapid technological and societal shifts may quickly alter emerging research trajectories.

Fifth, the Boolean search strategy, while systematic, may not capture all relevant studies employing alternative terminologies, theoretical framings, or emerging constructs within the entrepreneurship–STEM domain. Finally, although the authors maintained full intellectual control over all contributions, the use of AI tools during manuscript preparation may have introduced a degree of stylistic homogenization. However, this potential effect does not compromise the methodological rigor of the study or the validity of its empirical findings.

Future research can build upon this study by addressing the conceptual, methodological, and contextual gaps identified through bibliometric mapping. Mixed-methods designs that combine bibliometric analysis with systematic reviews, meta-synthesis, or qualitative case studies could provide deeper insights into how entrepreneurial competencies are interpreted, operationalized, and taught across diverse STEM education contexts. Expanding future analyses to include policy documents, practitioner reports, non-English literature, and additional databases (e.g., Web of Science, ERIC, and regional indexing systems) would offer a more comprehensive view of global scholarship. Moreover, future research should further examine how AI, sustainability imperatives, and interdisciplinary curriculum models influence the development of entrepreneurial mindsets within STEM education systems.

Author Contributions

Laurence C. Espino: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Formal analysis; Camille L. Espino: Data curation, Literature review, Visualization, Analysis, Writing – original draft, Writing – review & editing; Ronilo P. Antonio: Data collection, Validation, Writing – review & editing; Jovita E. Villanueva: Supervision, Project administration, Writing – review & editing; Lilibeth DG. Antonio: Proofreading, Project administration, Writing – review & editing.

Data availability statement

The datasets and replication files generated and analyzed during the current study are publicly accessible via Zenodo at: https://doi.org/10.5281/zenodo.17865826

Use of Generative-AI tools declaration

Details of AI use are provided in the Methodology subsection on the author's use of AI tools.

Conflict of interest

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this study.

Ethics declaration

This study used peer-reviewed literature from the Scopus database and involved no human participants or personal data. Formal ethics approval was not required.

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Author's biography

Dr. Laurence C. Espino is a professor of entrepreneurship and business administration from Bulacan State University, Philippines.

Dr. Camille L. Espino is a professor of science and teacher education from Bulacan State University, Philippines.

Dr. Ronilo P. Antonio is a professor of science and teacher education from Bulacan State University, Philippines.

Dr. Jovita E. Villanueva is a professor of teacher education from Bulacan State University, Philippines.

Dr. Lilibeth DG. Antonio is a professor of information technology from Bulacan State University, Philippines.