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Systematic Review

Traversing the Evolution of Research on Engineering Education for Sustainability: A Bibliometric Review (1991–2022)

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Abstract: Engineering education plays a pivotal role in cultivating the engineering capacity for sustainable development. Nonetheless, there has been no comprehensive review that examines sustainability as a distinct knowledge domain within engineering education. This review filled this gap by conducting a bibliometric review to document the research landscape, analyze the intellectual structure of the literature, and identify emerging research themes. The review sourced 2738 Scopus-indexed documents published between 1991 and 2022. Data analyses included descriptive statistics, co-citation analysis, and keyword co-occurrence analysis. The study identified consistent growth in research output and geographic diversity. Four predominant conceptual themes were identified in the literature: (1) Engineering Education Reform, (2) Engineering Competencies, Pedagogy, and Curriculum, (3) Curriculum Assessment and Benchmarks, and (4) Sustainable Technologies. Findings emphasize the need for defining precise engineering competencies related to sustainability, incorporating diverse teaching methods, and ensuring that sustainability learning outcomes align with changing industry norms, regulations, and accreditation criteria. The study also highlights a growing focus on the use of Industry 4.0 technologies as a means of achieving sustainability outcomes. The review underscores the need for sustained curriculum reform to successfully transform engineering education toward sustainability.

Keywords: engineering education; sustainability; sustainable development; education for sustainable development; higher education; systematic review; bibliometric review; science mapping

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1. Introduction

Sustainability is one of the foremost challenges of the 21st century [1–3]. The complex and interwoven nature of sustainability challenges requires global collaboration to find enduring solutions [2]. In response to this imperative, the United Nations General Assembly embraced a set of Sustainable Development Goals (SDGs) in 2015 [4,5]. The SDGs represent a collection of 17 interconnected, non-binding objectives envisioned as “a shared blueprint for peace and prosperity for people and the planet, now and into the future” [6].

These goals encompass a broad spectrum of economic, environmental, and social issues, including poverty alleviation, healthcare accessibility, infrastructure enhancement, education, gender equality, and resource management [7]. The discipline of engineering stands as a cornerstone supporting all SDGs [7]. Nonetheless, the degree to which engineering contributes to the achievement of these goals will, in turn, depend on the profession’s ability to reorient its approach to educating, training, and developing engineers [1–3,8,9].

To prepare future engineers for sustainable development challenges, educational institutions must equip them not only with technical knowledge but also with a diverse set of sustainability-oriented competencies and attitudes. These include skills in creative thinking, complex problem-solving, and interdisciplinary collaboration, as well as ethical dispositions [7,9,10]. To support this transformation, educators will benefit from an organizing framework encompassing quality assurance and accreditation processes that incorporate sustainable development values and goals [7]. Such a framework could also bolster efforts to develop more valid assessments of the skills and competencies of engineering graduates [7].

The progression of research in engineering education for sustainability is evidenced by the publication of several recent literature reviews [3,5,11,12]. For instance, Gutierrez-Bucheli et al. [5] conducted a scoping review that mapped and analyzed sustainability learning outcomes in engineering education. Mesa et al. [11] analyzed case studies and projects related to sustainability learning in engineering preparation programs. Mesa and Esparragoza [12] examined the literature on the implementation of circular economy initiatives in engineering education. Thürer et al. [3] reviewed the integration of sustainability criteria and content into undergraduate and postgraduate engineering education degree programs.

While these reviews yielded valuable insights, none examined the literature from the perspective of a 'knowledge base'. Thus, engineering educators lack a broad view of the scope of global research and the thematic structures that have evolved in the emerging knowledge base on engineering education for sustainability.

This research review addressed these knowledge gaps by systematically exploring and synthesizing the Scopus-indexed literature on engineering education for sustainability. The review aimed to analyze the research landscape, its thematic evolution, and the forces shaping its trajectory. Three research questions guided this review:

1. What is the research landscape concerning sustainability in engineering education, considering factors such as document volume, growth trends, and geographical distribution?
2. What is the intellectual structure of the literature on engineering education for sustainability?
3. How have the topical foci of research on sustainability in engineering education changed over time, and what are the high-priority topics being studied in the recent literature?

This review identified 2738 relevant Scopus-indexed documents on engineering education for sustainability published between 1991 and 2022. Bibliographic data were analyzed using Scopus analytical tools, Microsoft Excel, Tableau, and VOSviewer software (Version 1.6.18) programs. The data analyses employed descriptive statistics, co-citation analysis, and keyword co-occurrence analysis.

This bibliometric review offers the first comprehensive analysis of the full Scopus-indexed literature on engineering education for sustainability. The review was designed to complement previously published research reviews on engineering education for sustainability [3,5,11,12]. Furthermore, this review of research is positioned to provide empirical reference points for future research and shed light on prospective directions for research and practice.

2. Method

The present study adopted bibliometric review methods to analyze trends in the research on engineering education for sustainability [13]. Bibliometric review provides a transparent and reproducible process that reduces subjective bias in identifying and analyzing a body of knowledge [13,14]. This differs from other review methods (e.g., scoping, integrative, meta-analytic) in that it does not aim to synthesize past research findings. Instead, bibliometric reviews analyze bibliographic associated with a set of documents in order to gain a broad perspective on the composition of a knowledge base [14,15].

2.1. Identification of Sources

This review relied on Scopus to identify documents, a choice substantiated by comparative studies [16,17] that evaluated document databases. These studies revealed that Scopus offers broader journal coverage than Web of Science [18]. While Dimensions and Google Scholar are also comprehensive, they include non-peer-reviewed articles [18]. Additionally, the application of co-citation analysis made it possible for this review to access extensive literature outside of Scopus.

An open-ended search strategy was employed using the following search string: (TITLE ((“engineering education” AND (sustainability or “sustainable development”) OR KEY (“engineering education” AND (sustainability or “sustainable development”)). The search was not limited in terms of publication year, geographic location, or document type. The initial search yielded 2865 Scopus-indexed documents. Variations on this search were conducted to ensure comprehensive coverage of as many relevant documents as possible.

The review database was identified, screened, and selected using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [19]. As shown in Figure 1, Scopus filters limited the Scopus list to refereed conference papers, peer-reviewed journal articles and reviews, books, and book chapters published through the end of 2022. Since it was necessary to review some critical publications, the database was restricted to English-language documents. Finally, duplicate documents were removed based on a screening of publication titles. The final review database comprised 2738 Scopus-indexed conference papers, journal articles and reviews, books, and book chapters published between 1991 and 2022.

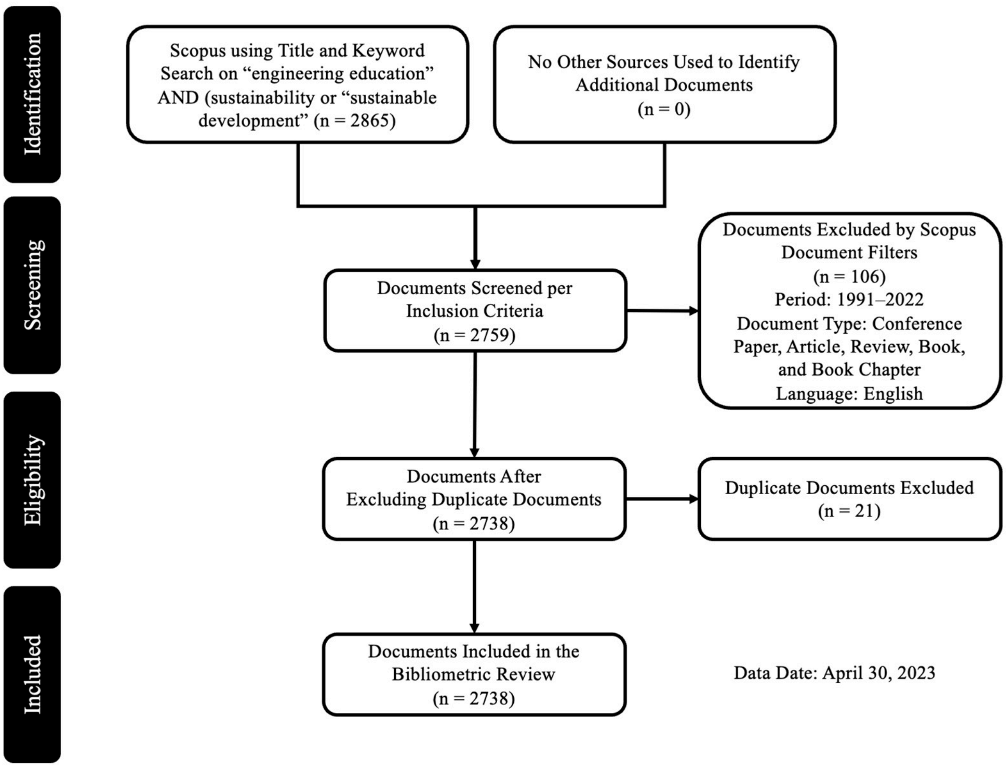

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [19].

2.2. Bibliometric Data Analysis

The authors exported bibliographic data associated with the documents from Scopus to an Excel file. Ambiguities in the data file were identified and resolved using VOSviewer version 1.6.19 to ensure accuracy [20]. A thesaurus file (i.e., a data disambiguation instruction file) was created and uploaded with the data file in VOSviewer software to detect and consolidate alternative keywords or name forms [20].

The first research question was addressed using Scopus analytical tools, Microsoft Excel, and Tableau. The authors utilized the software programs to chart the document volume, growth trends, and geographical distribution of the knowledge base.

For the second question, author co-citation analysis in VOSviewer was used to visualize the intellectual structure—theoretical themes or lines of inquiry—of research on engineering education for sustainability [13,21,22]. The analysis analyzed the frequency of author citations, as well as the "co-citation" of pairs of authors in the same reference lists. Subsequently, VOSviewer was used to create an author co-citation network map that visualized the relationships of authors cited in the reference lists of the review documents [15]. Co-citation analysis assumes that authors who are frequently co-cited in the same documents often share a common theoretical orientation [13,14,21]. The authors synthesized patterns in author relationships on the network map to identify the intellectual structure of the literature [13,14].

The third research question was explored through keyword co-occurrence analysis (co-word analysis), also carried out in VOSviewer [15,23,24]. First, keyword analysis was employed to pinpoint the most prevalent keywords associated with the review documents. This analysis yielded insights into the topics that have garnered significant attention in the literature on engineering education for sustainability [25].

Next, the authors used VOSviewer to construct a co-word network map with a temporal overlay that visualized connections among various keywords and topics [13,23,24]. Similar to co-citation analysis, co-word analysis examines the 'co-occurrence' of pairs of keywords within the reviewed documents, offering insights into keyword relationships based on frequency and occurrence patterns. The temporal co-word network map was also created to visualize the evolution of themes within the literature over time. In this analysis, VOSviewer analyzed the distribution of publication dates associated with keywords extracted from the review documents [13,15,20]. This enabled the authors to analyze the topical development of the literature and identify emerging topics [13,26].

3. Results

3.1. Descriptive Analysis of the Review Database

The 2738 Scopus-indexed documents in the review database were comprised of conference papers (73%), peer-reviewed articles and reviews (24%), book chapters (2%), and books (1%) published between 1991 and December 31, 2022. The trend lines in Figure 2 show that interest in sustainability among engineering educators emerged gradually, with an average of 11 indexed documents published annually during the 1990s. The annual rate of publication increased to 64 publications per year between 2000 and 2010 and 166 from 2011 through 2022. Nearly 90% of the literature has been published since 2005 (see Figure 2). Increased interest could have been stimulated by the United Nations' proclamation of the Decade of Education for Sustainable Development in 2005 [3,27].

The Scopus-indexed literature on engineering education for sustainability includes publications from scholars located in 104 nations. Seventy-five percent of the publications originated in developed nations, and 25% in developing societies. Scholars from the United States (37%), Europe (37%), and Asia (18%) largest contributed most substantially to this knowledge base (see Figure 3).

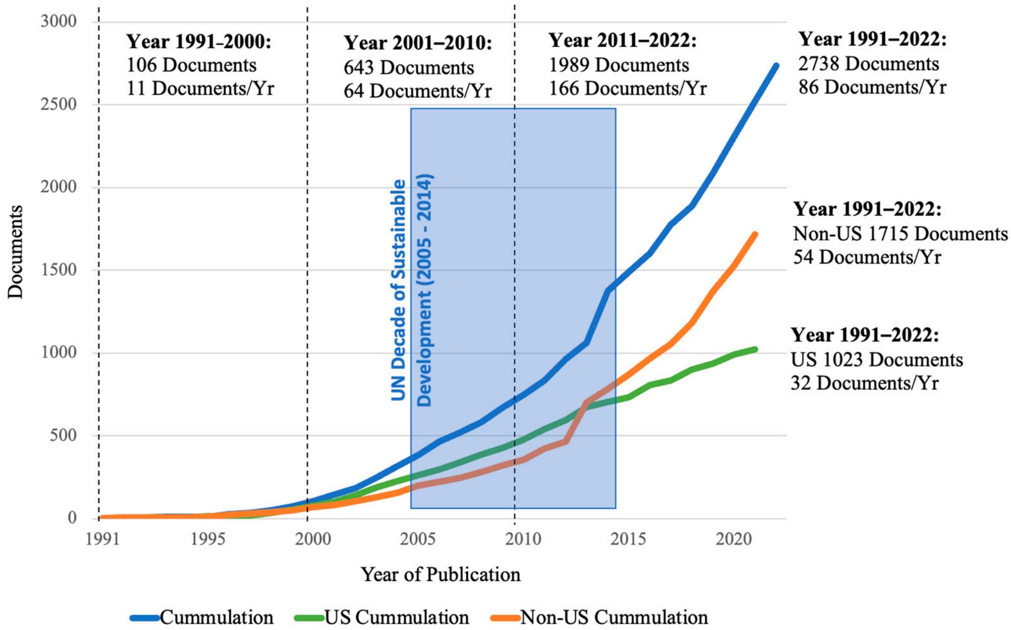

Figure 2. The growth trajectory of Scopus-indexed publications on engineering education for sustainability, 1991–2022 (n = 2738).

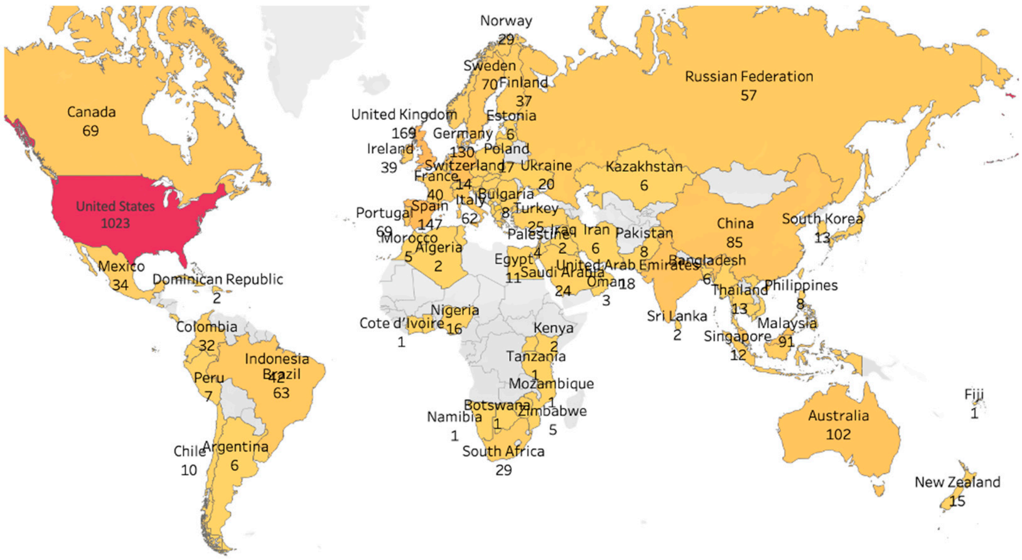

Figure 3. Geographical distribution of Scopus-indexed publications on engineering education for sustainability, 1991–2022 (n = 2738). Map created in Tableau software (https://www.tableau.com/).

3.2. *Intellectual Structure of Research on Engineering Education for Sustainability*

VOSviewer was used to generate an author co-citation network map containing 144 influential authors (see Figure 4). Node size in the network map suggests the citation frequency of an author in the reference lists of the review documents. Both the density of links and the proximity between authors reflect the degree of intellectual affinity [15]. Colored clusters on the network map represent the 'schools of thought' [13] that comprise the intellectual structure of this literature [14,22].

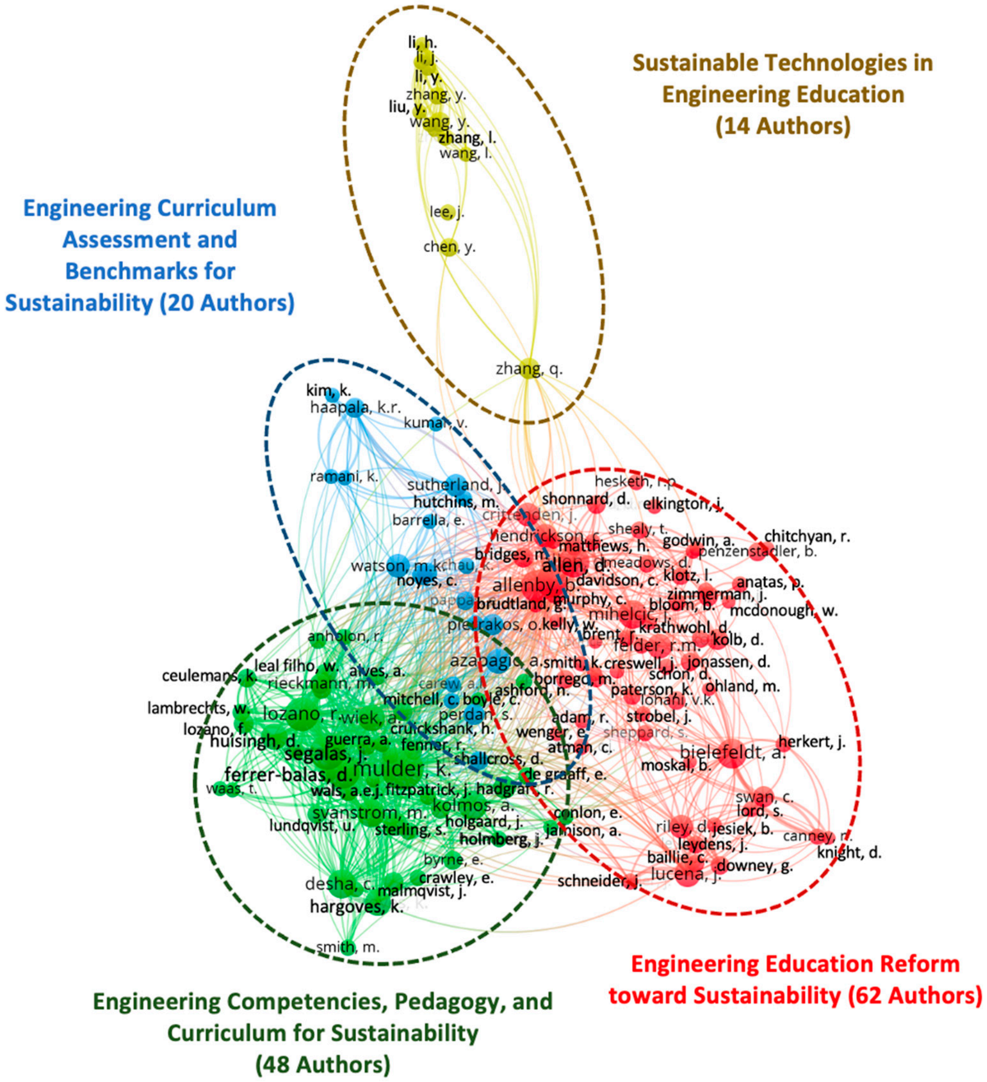

Figure 4. Author co-citation network map on engineering education for sustainability, 1991–2022 (Threshold = 38, display 144 authors). Map generated in VOSviewer.

As shown in Figure 4, the co-citation network map visualizes four clusters of authors based on their patterns of co-citation by other scholars. The four schools of thought include (1) Engineering Education Reform toward Sustainability, (2) Engineering Competencies, Pedagogy, and Curriculum for Sustainability, (3) Engineering Curriculum Assessment and Benchmarks for Sustainability, and (4) Sustainable Technologies in Engineering Education. The intellectual foci of the four schools were identified by examining the publications of the affiliated authors [13].

The largest school (red cluster) is comprised of 62 authors who have focused on Engineering Education Reform toward Sustainability. This school is led by Allenby (193 co-citations), Allen (179), Davidson (175), Bielefeldt (158), Mihelcic (148), Lucena (128), Felder (117), Hendrickson (104), Crittenden (101), and Riley (101). Scholars in this school have been among the most active proponents for incorporating sustainability into engineering education programs [28–30]. Their research reflects the growing societal attention to environmental issues and increased funding for measures to support sustainable engineering [31,32].

Scholars in this scholarship have explored challenges and barriers to the successful integration of sustainability in engineering education curricula [33–37]. This includes the difficulty of displacing existing curricular objectives [33,34], lack of resources, suitability of existing teaching methods and materials [34,35,37], and a lack of familiarity with social dimensions of sustainability in engineering [33,35].

In response, they have proposed instructional strategies such as empowering participants through guided practice and providing learning activities and tools that can be tailored to the unique learning environments of particular institutions [35–37]. Approaches include incorporating sustainable engineering principles into elective and core courses [33,38,39], fostering educational innovation through student-to-student networks between partner universities [38], and cultivating faculty expertise through the development and dissemination of learning materials and practices [37,38].

Scholars in this school have also investigated ethical and social issues taught in engineering education programs [40–43]. This research highlights a need for engineering programs to promote attitudes and practices that prioritize the safety, health, and welfare of the public [42]. Cultural influences on ethics-related education outcomes have also been explored, comparing the teaching of ethics in programs from different countries [40,43].

The second largest school of thought (green cluster) is comprised of 48 authors associated with Engineering Competencies, Pedagogy, and Curriculum for Sustainability. This school is led by Mulder (330 co-citations), Segalàs (224), Lozano (200), Ferrer-Balas (198), Desha (146), Kolmos (143), Svanström (136), Wiek (126), Huisingh (122), Hargroves (101), and Sterling (107). These researchers have emphasized the importance of defining the desired attributes and competencies of engineering graduates prior to redesigning the curriculum and selecting pedagogical methods aimed at enhancing sustainability outcomes [8,44–47]. Moreover, their research highlights the need to develop an engineering program's vision of sustainability based on input and standards from industry, accreditation bodies, and professional societies [8,44,46]. They also advocate for alignment with the Sustainable Development Goals [8,47,48] as a guiding framework for incorporating sustainability into engineering education.

Researchers in this school have explored a range of relevant pedagogical strategies, including problem-based learning, project-based learning, team-based learning, and community service learning [49–53]. Educators have also experimented with other active learning approaches, such as challenge-based learning [54,55], design-based learning [56,57], and inquiry-based learning [58,59]. The use of these methods has been motivated by the desire of engineering educators to engage learners in real-world problems and apply knowledge to a broader set of educational outcomes.

Lastly, studies in this school have examined the renewal of engineering curricula and the development of educational capacity for sustainability-oriented teaching and learning [3,60–63]. These studies have focused on industry engagement, instructor skill enhancement, and the development of curriculum and teaching resources [60,62–65]. This research has identified a need for timely engineering curriculum renewal to keep pace with changes in industries, regulations, and accreditation standards [61,65,66].

The third school (blue cluster) includes 48 authors associated with Engineering Curriculum Assessment and Benchmarks for Sustainability. This school is led by Azapagic (103 co-citations), Watson (102), Sutherland (93), Perdan (84), Pierrakos (84), Haapala (74), Noyes (71), Rodgers (71), Pappas (68), and Shallcross (60). Scholars located in this school have focused on evaluating the effectiveness of efforts to embed sustainability into engineering education programs [67–72].

Their studies have utilized surveys to evaluate students' development in conceptual knowledge, design capabilities, and attitudes toward sustainability [67–69,71]. This research has validated survey scales and scoring rubrics for use in assessing students' knowledge, skills, and attitudes [67,71]. For example, the Sustainability Tool for Assessing University's Curricula Holistically (STAUNCH®), Sustainable Design Rubric, and Concept Maps have been employed to gauge the impact of engineering courses on key learning outcomes [67–69,71–73]. The findings suggest that while students accept the importance of sustainability values and goals in engineering, they encounter challenges in applying a sustainability mindset to engineering practice [74–76].

Surveys have also assessed the integration of sustainability topics in engineering education programs [68,74]. These surveys have revealed a predominant emphasis on the relationship between engineering and the environment, with less attention on the social and economic dimensions of sustainable development [68,74]. Moreover, engineering students often lack familiarity with environmental legislation, policy, and standards [74]. This underscores the need for more systematic and balanced coverage of sustainability-related topics within the engineering curriculum.

The fourth school (yellow cluster) includes 14 authors associated with Sustainable Technologies in Engineering Education (STEE). At the forefront of this cluster is Q. Zhang (80 co-citations), followed by Y. Wang (69), Y. Chen (64), Y. Zhang (55), J. Lee (53), J. Li (52), X. Wang (49), L. Zhang (47), L. Wang (44), and Y. Liu (41). The STEE cluster is located at a greater distance and shows fewer author co-citation links to the other three clusters. These visual features highlight the distinctive nature of this school of thought, comprised predominantly of Chinese authors.

These scholars have studied the efforts of engineering programs to integrate new technologies designed to reduce carbon emissions and promote clean energy [77–79]. This research has also examined curricular approaches that focus on industry responses to environmental regulation [80–82] and the implementation of sustainable manufacturing [83,84]. Findings from these studies underscore the role of government support, industry partnerships, and interdisciplinary collaboration when engineering programs seek to incorporate cutting-edge innovations [78,80,85–87].

Research in this domain has also explored the transformative impact of information and communication technology (ICT) on sustainability-focused engineering education, particularly in the development of smart campuses [85,88,89]. Scholars have identified five ICT drivers behind this change [85]: (1) data computing and storage technologies (e.g., cloud and edge computing) [90,91]; (2) Internet of Things technologies (e.g., smart sensors and communication protocols) [92–94]; (3) intelligent technologies (e.g., artificial intelligence, machine learning, and computation intelligence) [95–97]; (4) immersive technologies (e.g., augmented and virtual reality) [98–101]; and (5) mobile technologies (e.g., mobile phones and tablets) [100,102]. These studies shed light on the transformative potential of these technologies, offering data-driven insights into their pivotal role in shaping the future of sustainability-focused engineering education programs.

The concentration of Chinese scholars in this school suggests the significant emphasis Chinese policymakers have placed on leveraging innovative technologies to tackle sustainability challenges [4,78,85,86]. Notably, the network map highlights both the physical isolation of this school as well as limited connections between the Chinese scholars and scholars in the other schools. These features of the network map suggest that, to some extent, this school is evolving in parallel with the other schools. The field will benefit from strengthening these linkages.

3.3. Topical Analysis of Engineering Education for Sustainability

The final research question was tackled through keyword co-occurrence analysis (co-word analysis) conducted in VOSviewer [15,23,24]. In the first step, the authors identified the most frequently occurring keywords in this literature. These included engineering curriculum (2631 occurrences), curriculum development (854), professional competencies (279), distance learning (199), education computing (196), education systems (191), environmental problems (179), project management (165), product design (161), surveys (158), societies and institutions (156), pedagogical approach (149), higher education (146), personnel training (140), design (129), economic and social effects (128), innovations (127), technical presentation (125), problem-solving (124), computer-aided instruction (119) and multi-disciplinary (117). These keywords offer insight into the sustainability-related topics most frequently studied by engineering educators.

Next, a temporal co-word network map [13,15] was created using VOSviewer (see Figure 5). When creating the network map, the authors used a threshold of 26 keyword occurrences to strike a balance between frequency (i.e., popularity) and comprehensiveness of topical coverage [25]. Similar to the co-citation network map, the size of the nodes representing keywords on the co-word network map corresponds to the relative frequency of their appearance in the document list. Links and proximity among the keywords are also interpreted using similar guidelines. On this network map, the color coding of keywords reflects the relative recency of scholarly interest in the topics. The brighter-colored keywords are associated with topics of most recent interest. Darker-colored keyword nodes are associated with topics that were more popular in past decades. Thus, the temporal co-word network map highlights keyword recency, frequency, and relationships.

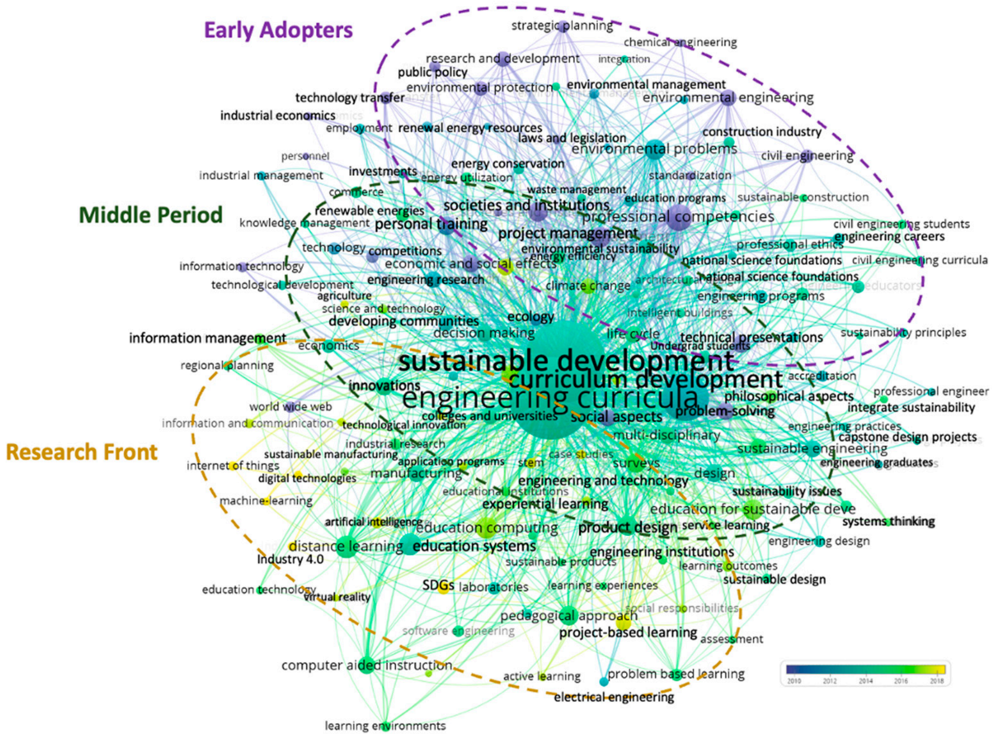

Figure 5. Co-word network map with a temporal overlay on engineering education for sustainability, 1991–2022 (Threshold of 26 occurrences, display 147 words from 13,085 keywords). Map generated in VOSviewer.

The temporal co-word network map presents the evolution of research on sustainability in engineering education in terms of three distinct periods. These were labeled 'Early Adopters' (1990s–2000s), 'Middle Period' (2005–2015), and the 'Research Front' (2016–2022). It should be noted that the time periods are only approximations. This is because, in temporal co-word analysis, VOSviewer creates a 'time distribution' for each keyword based on the publication years of its associated documents. Thus, for example, a keyword with a yellow node has a distribution that is centered during the most recent period.

In the Early Adopters period, represented by the dark purple nodes, researchers primarily directed their attention toward identifying the professional competencies required by engineers to effectively address sustainability challenges. For example, they identified the following knowledge, skill, and attitude domains: interdisciplinary knowledge, holistic and integrative approaches, critical and systems thinking abilities, effective collaboration and communication skills, creativity and innovation, capacity for change, and ethical responsibility [103–105]. During this period, researchers tended to concentrate on the integration of sustainability into specific engineering subjects such as project management, civil engineering, environmental engineering, and chemical engineering [106,107]. This research tended to focus on undergraduate engineering education [108,109].

During the Middle period, denoted by dark and light green nodes, scholars tended to focus on topics related to pedagogy and curriculum development for sustainability [49,52,60,61,110]. For example, significant research began to accumulate on the use of problem-based learning, project-based learning, team-based learning, and community service learning in teaching and learning for sustainability in engineering programs [49,52,53,110]. This period also witnessed an expansion of engineering education for sustainability into new fields, including manufacturing, electrical engineering, and software engineering [111,112]. Concurrently, educators evidenced increasing interest in environmental sustainability topics such as climate change, energy efficiency, and renewable energy [112–114]. Additionally, this phase of research showed growing attention toward the integration of sustainability topics into capstone and first-year engineering courses, as well as the exploration of distance learning methodologies [114,115].

The network map shows that the 'research front' (yellow nodes) is concentrated at the intersection of sustainability, engineering education, and Industry 4.0 technologies. This research has explored the application of artificial intelligence, the Internet of Things, machine learning, and virtual reality to advance environmental, social, and economic sustainability [96,116–118]. Notably, the surfacing of these topics reprises the yellow cluster on the author co-citation network map, which focused on sustainable technologies. This body of research delves into the integration of sustainability principles through the lens of Industry 4.0 technologies [116,119,120]. This encompasses various facets, including the development of inclusive learning environments tailored for Industry 4.0 adaptive learners and the sustainable utilization of digital technology in long-term teaching strategies [119,120]. Lastly, these studies address the barriers, challenges, and opportunities associated with the incorporation of digital technology into sustainable manufacturing practices [120,121]. Supplementary Materials files can be accessed through the link provided under the sub-heading "Supplementary Materials".

4. Discussion

In this concluding section, the authors acknowledge the limitations of our review, synthesize the key findings, and highlight implications for future research and practice.

4.1. Limitations of the Review

The initial limitation stems from relying on Scopus as the sole source for review documents. While Scopus is recognized for its comprehensive coverage of educational literature [16–18], it is important to acknowledge that it may not encompass every potentially relevant document. Nonetheless, the analysis of the 2738 documents in this review represents a substantial sample of published research on engineering education for sustainability and the largest body of documents featured in any bibliometric review of this literature identified at the time of this study [122,123]. That being said, future studies could enhance the comprehensiveness of this research review by incorporating other review databases to identify eligible documents.

The second limitation arises from the inconsistent use of terminology associated with sustainability or sustainable development within engineering education [124,125]. This limitation could have resulted in the inadvertent exclusion of pertinent documents that utilized alternative, less-frequently-used terms (e.g., environmental stewardship, renewability, and eco-friendliness). Subsequent research endeavors could broaden the review by incorporating additional search terms, thereby balancing comprehensiveness and inclusivity.

The third limitation is tied to the quantitative methodology employed in this review. As previously mentioned, this study neither assessed the quality of individual studies nor their findings. Consequently, the insights derived from bibliometric analysis complement the results of other reviews. Future qualitative research reviews, such as scoping reviews, can also offer additional and valuable perspectives on the knowledge base.

4.2. Interpretation of the Results

The descriptive analyses conducted for this review described the evolving landscape of research on sustainability in engineering education. The fact that nearly 90% of the sourced publications have emerged since 2005 underlines the growing relevance of sustainability issues in the engineering profession. Moreover, this body of literature represents a global effort. Scholars from the United States, Europe, and Asia, especially China, have played pivotal roles in shaping this discourse. However, the dominance of developed nations in contributing to this knowledge base suggests a need for additional focus on educational trends in developing societies. This will ensure that the knowledge base on sustainability education in engineering yields solutions that are relevant to societies throughout the world.

The author co-citation network map revealed four distinct clusters of authors who evidenced shared intellectual affiliations. These four schools of thought encompass (1) Education Reform Toward Sustainability, (2) Engineering Competencies, Pedagogy, and Curriculum for Sustainability, (3) Engineering Curriculum Assessment and Benchmarks for Sustainability, and (4) Sustainable Technologies in Engineering Education. The identification of these schools of thought provides a set of rubrics that educators can use to guide not only their reading of the literature but also future research and development activities.

The relevance of these intellectual foci was reinforced by the co-word network map, which featured many similar co-occurring keywords derived from the text of the documents. For example, take the second school of thought, Engineering Competencies, Pedagogy, and Curriculum for Sustainability. The co-word network map highlighted frequently co-occurring keywords such as engineering curricula, curriculum development, professional competencies, pedagogical approach, project-based learning, problem-based learning, learning experiences, active learning, and experiential learning. The emergence of these keyword patterns on the co-word network map offers additional credibility to the authors' interpretations of the author co-citation network map.

Together, the co-citation and co-word analyses underscore several priorities for advancing the integration of sustainability in engineering education. These include the necessity of defining clear sustainability-related competencies needed by practicing engineers, exploring diverse pedagogical approaches, and regularly updating curricula to enhance sustainability learning outcomes and align with evolving industry trends, regulations, and accreditation standards [49,52,61,65,66].

The conjoint findings also highlight the increasingly important role that technology will play not only in developing engineering solutions to sustainability challenges [77,78,97] but also in the delivery of engineering education for sustainability [57,88,112,119]. Specifically, the current research trajectory within this field seems to concentrate on the effective utilization of Industry 4.0 technologies to attain sustainable development goals, bolster sustainability in manufacturing processes, and cultivate innovation competencies within engineering education [117–119]. These findings emphasize the importance of incorporating these elements into educational strategies and curricular innovations in engineering programs.

Lastly, this review of research uncovered significant challenges and potential solutions for integrating sustainability into engineering education curricula [37,85,91,120]. The obstacles include the complexities of replacing existing content, resource limitations, a limited understanding of sustainability's social and economic dimensions, and the practical application of sustainability principles in engineering practice [12,72,107]. Scholars have also put forth strategies such as guided practice and tailored tools for diverse institutional environments. They advocate for the infusion of sustainable engineering principles into core and elective courses, promoting innovation through inter-university collaboration, and enhancing faculty expertise via resource sharing [37,38,70]. Collaboration with industry, accreditation bodies, and professional societies is also seen as crucial to overcoming these challenges and advancing sustainability in engineering education [61,65,66].

4.3. Implications of the Findings

The geographic concentration of this review database in developed nations emphasizes potential disparities in access to engineering education. This also highlights the immediate need for international collaboration and knowledge exchange in enhancing sustainability education. Indeed, educators in both developing and developed nations can gain valuable insights through international partnerships [126,127]. The potential benefits of this type of mutual exchange can also foster inclusivity and comprehensiveness in sustainability education, contributing to a more equitable and sustainable future.

This was particularly evident in the domain of sustainable technologies. While the author co-citation network map revealed intellectual leadership in this domain by Chinese scholars, connections with scholars elsewhere in the world were quite sparse. This highlights an urgent need for collaboration so that engineering programs elsewhere in the world can learn from their experiences.

The identification of four distinct schools of thought within sustainability in engineering education offers a roadmap for future research and curriculum development. These clusters encompass essential dimensions of sustainability education, such as the reform, development, and assessment of engineering curricula and the integration of advanced technology. Researchers and educators should consider these clusters as foundational elements when designing sustainability-focused curricula and pedagogical approaches, aiming to produce well-rounded engineers capable of addressing sustainability challenges effectively.

The intellectual clusters further underscore the importance of continuous research on the integration of sustainability within engineering education. Specifically, researchers must delve deeper into individual clusters while exploring intersections and synergies between them to foster a more integrated, comprehensive, and well-balanced approach to sustainability education. These clusters also serve as valuable resources for educators seeking to enhance sustainability education in their engineering programs, enabling institutions to develop more effective strategies for integration.

Notably, this research review did not uncover themes related to the theoretical foundation in engineering education for sustainability. This is in line with findings from prior reviews, which found limited use of theoretical and model-driven frameworks [9]. Additionally, the decision-making processes for education for sustainability in engineering heavily rely on policy recommendations and practitioner intuition [128]. This underscores the need for future research to adopt a theoretical and model-driven approach to elucidate this unique phenomenon and provide insights to guide subsequent studies and practices in the field of sustainability within engineering education.

The results of the analyses further offer significant implications for the advancement of sustainability education in engineering. Firstly, the findings reinforce the continuing need to define and refine engineering competencies in sustainability education [1,8,44,103,119]. This implies that educational institutions and engineering programs should clearly articulate the knowledge, skills, and attitudes students need to develop in sustainability-related areas [56,104,105,129]. Secondly, the emphasis on diverse pedagogical approaches highlights the importance of innovative teaching methods to engage students in addressing sustainability challenges [53,54,56,69,124]. Engineering educators should explore various strategies and combinations of strategies to make sustainability education more engaging and impactful [49,50,55,57,58].

Thirdly, the regular updating of curricula to align with industry trends, regulations, and accreditation standards is imperative. This implies that engineering programs should maintain flexibility and adaptability to ensure students are well-prepared for evolving sustainability challenges in their future careers. Fourthly, the integration of technology, particularly Industry 4.0 technologies, underscores the potential of digital tools and approaches to enhance sustainability education. Engineering institutions should invest in technological resources and training now to leverage these advancements for better sustainability learning outcomes. Considering the heightened focus on Industry 4.0 technologies, it is also recommended that a more comprehensive exploration of upcoming trends be conducted. This examination should delve into how these technologies might persist in influencing sustainability within the realm of engineering education.

Finally, this research review highlights the need to address challenges impeding the seamless integration of sustainability principles into engineering education. To overcome these barriers, considerable investments, well-structured policies, and robust support from industry, government agencies, and higher education institutions are necessary. Mainstreaming sustainability throughout engineering programs, encompassing both core and elective courses, is also essential to equip all students with a comprehensive understanding of sustainability's relevance [5,33,44,103]. Additionally, fostering collaboration with industry, accreditation bodies, and professional societies is vital for aligning engineering education with industry standards and accessing valuable guidance and resources, ensuring that graduates are prepared to contribute to a more sustainable and equitable future.

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