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Review

A scientometric analysis of information technology in sustainable higher education: knowledge structure and frontier trends

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Abstract
Achieving quality education by providing equitable resources and promoting lifelong learning has attracted scholarly attention since the United Nations proposed Education for Sustainable Development (SDG4) in 2015. The transformation of information technologies has dramatically advanced the fulfillment of SDG4 by revolutionizing communication and learning processes. Updated research to trace the evolution of the relevant field will boost researchers executing ground-breaking research for improving the domain. By utilizing the bibliometric analysis with CiteSpace, this research investigated knowledge structures and frontier trends regarding information technology in sustainable higher education, which included 5370 documents primarily retrieved from the Web of Science between January 2010 and December 2022. The findings indicated that web-based online learning, transparent and unified sustainability reporting criteria, and sustainable campus administration with the assistance of information technologies had drawn significant attention. The most promising topics include: utilizing information technology to improve students' cross-cultural competencies; adjusting curriculum content for the dynamic changing environment; collaborating between different participants to obtain a circular economy; and the priority of enhancing pedagogy competence of teachers. The results provide crucial insight to researchers via graphical expression, thus facilitating a comprehensive understanding of the field, shedding light on topics not thoroughly explored in this knowledge discipline, and providing valuable direction for future research.

Keywords Scientometrics · Information technology · Sustainable higher education · Citespace

1 Introduction

In the era of the Fourth Industrial Revolution, the utility of information technology (IT) in the education sector has increased as the subject which received extensive attention from scholars [1, 2]. According to the Sustainable Development Goals (SDG4) for Quality Education proposed by United Nations, higher education institutions are excellent mediums for alleviating poverty, ensuring inclusive education, and fostering learning opportunities [3]. Internet-based interaction and instructional tools, such as online-learning platforms, MOOCs, and virtual reality technologies, have become indispensable tools in promoting sustainable learning, enabling learners to meet their needs effectively in a constantly evolving economic and social environment. For instance, the global adoption of MOOCs, which refers to massive open online courses, has occurred in parallel with the improvement and innovation of information technology, especially in universities. Altalhi [4] conducted research to assess the factors determining students' acceptance of MOOCs at Taif University in Saudi Arabia, whereas Meet et al. [5] explored factors affecting the adoption of MOOCs in Generation Z. Similarly, two studies by Althunibat [6] and Chahal and Rani [7] investigated the factors influencing the

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intentions of mobile-learning and e-learning usage among the students of higher education institutions in Jordan and India, respectively.

Scientific research regarding IT in sustainable higher education is interdisciplinary, underpinned by different disciplines, such as psychology [8], computer science [9], and education pedagogy [10] while applying either quantitative methods [11] or qualitative methods [12]. According to Chaka [13], technological advances have evolved into crucial tools for achieving quality education and addressing various societal requirements by changing how education is delivered. Additionally, due to factors like their low cost or flexibility, IT contributes to eliminating social and economic inequalities that may exist in society and support the inclusion of everyone, given that there is equality of opportunity [14]. Moreover, the importance of promoting digital education tools for fostering critical thinking and transformative learning competencies also attracted scholars' attention. Meirbekov et al. [15] examined the potential and effectiveness of digital technologies for developing educators' and students' critical thinking. The research emphasized that encouraging critical thinking, metacognitive awareness, and cognitive learning is crucial for sustainable educational development. Obviously, there is growing international recognition that Education, notably higher education institutions, is a crucial enabler for sustainable development [16]. Information technology and digital tools have become indispensable in achieving this objective by minimizing social and economic inequities, reducing the information gap, and promoting the inclusion of all people [17].

1.1 Literature review

With the significant development of information technology, an increasing number of studies have explored IT-assisted research areas [18], education-related research areas [19], and integrated scientific research involving relationships between IT and education [20]. Information Technologies have significantly contributed to economic, social, and ecological development, drastically transforming how people communicate and live [21]. Obtaining quality education as a fundamental human right is essential in eradicating poverty and creating learning opportunities, as established in the objectives for SDG4 [22] for sustainable development. Moreover, in the era of Education 4.0, which refers to the globally connected and dynamic updating information environment, the holistic, integrated, interdisciplinary education process can only be realized with the help of information technology [23].

Rawat and Sood [24] reviewed the scientometric features of publications from 2011 to 2020 regarding computer applications in education. It identified that higher education with the application of ICT had experienced the latest research trend and involved designing frameworks for promoting student performance and the education process. On this basis, Sood and Rawat [20] also highlighted the importance of ICT-assisted technologies for disaster-related education in higher education.

Additionally, groundbreaking technologies make learning more convenient, collaborative, and individualized [23]. For instance, by leveraging web-based technologies and online learning platforms, students can obtain information and knowledge almost free of cost without the time and location constraints, communicating and interacting with educators, which is also consistent with the philosophy of SDG4 [25]. According to [26], the education sector has widely adopted innovative technologies like the Internet of Things, cloud computing, and big data in practice. For instance, universities currently provide services such as University-as-a-Platform (UaaP), Education-as-a-Service (EaaS), and Internationally-linked Programs to encourage and stimulate a more efficient and engaging learning process for students [27]. Moreover, in recent years, literatures based on bibliometric analysis methods using scientific mapping tools have rapidly emerged in various disciplines and topics, such as the 3-D printing technology domain [18], epidemiology [28, 29], public finance sectors [30], and education [31]. The high frequency of applying Citespace in the bibliometric analysis is because of its outstanding features, such as enabling the researchers to track the growth of scientific research over time [20].

1.2 Research gap

Although existing literature has provided overviews regarding IT-assisted technologies in education, more specific research on subfields in higher education is relatively scarce, especially combined with the concept of SDG4, which was officially introduced to the public in 2015 [22] and then given a further explanation in 2017 [3]. Previous literature was conducted in isolated investigations, discussing related topics separately. The overviews of the relationship between IT and sustainable higher education are often overlooked. This study is an essential complement to the subfields of education-related domains.

Additionally, IT was considered a catalyst for disruptive educational innovation in learning and education [19]. Thus, conducting an updated and synthesized bibliometric review of scientific investigations is essential to understand how these integrated fields promoted mutually and evolved over the years.

1.3 Objectives

To explement the previously noted paucity and facilitate further research on IT in sustainable higher education, this paper aims to present an integrated, comprehensive literature review on the knowledge-evolution process of this emerging topic. Using computational and visual analytic approaches with information visualization provided by Citespace, it reveals the knowledge structures of the domain, including overall publication trends, the knowledge flow of disciplines, the intellectual bases of research specialties, the research milestones and focuses, the dynamics of transitions, and the potential promising research areas for scholars. The main contributions of this paper include the following:

- Provide updated and computationally assisted literature reviews of IT-related research themes in sustainable higher education, summarizing the knowledge base and thematic development in detail.
- Provide a better understanding of the intellectual base, milestones, research fronts, and emerging trends for further study.
- Verify a reliable search strategy for indexing original data since a high-quality dataset retrieval provides a solid basis for further computation and visualization.

1.4 Research design

The workflow of the research design is shown in Fig. 1.

In the following sections, Sect. 2 covers the research methodology and data collection process, which shows how to create a representative dataset of bibliographic records using a general search method. Section 3 provides the primary scientometric analysis, including publication trend, dual-map analysis, co-occurring analysis, co-citation analysis, and SVA of citation trajectories. The findings and discussion will be outlined in Sect. 4, along with the conclusions in Sect. 5; and potential directions for further research in Sect. 6.

2 Methods

2.1 Sample and data collection

The latest data [32] shows that the Web of Science Core Collection contains over 21,000 journals, books, and conference proceedings across over 250 disciplines, with nearly 85.9 million records. These world-class academic publications, such as scientific articles, reviews, and proceeding materials, provide a solid foundation for high-quality research samples [30].

Bibliographic records were initially retrieved from the Web of Science Core Collection on 03 February 2023 with a timespan from January 01, 2010, to December 31, 2022. A total of 5370 records were collected from WoS Core Collection, incorporating Social Sciences Citation Index (SSCI), Science Citation Index Expanded (SCI-EXPENDED), and Arts & Humanities Citation (A&HCI). The output data included all bibliographic information, including title, author, abstract, keywords, publication year, and cited references. The rationale of the query can be explained in Table 1. Parameters such as time slice, node type, selection criteria, and pruning method should be selected to fulfill various research objectives. Table 2 displays parameter values in detail.

2.2 Analysis and visualization tool

CiteSpace (V6.1.R6.) is employed for data analysis and visualization based on bibliographic records, effectively allowing big data measurement to explore the knowledge-evolution process of one domain or discipline [33]. Although several visualization tools are commonly used for scientific mapping analysis, including CiteSpace [20], Vosviewer [34], and Gephi [35], CiteSpace is the preferred and compatible software for analyzing WoS data since it does not require extra conversion procedures [28]. CiteSpace can produce diagrams considering the time factor, highlighting hotspots and research subfields based on temporal trends [36]. This feature can assist researchers in identifying the evolution process with

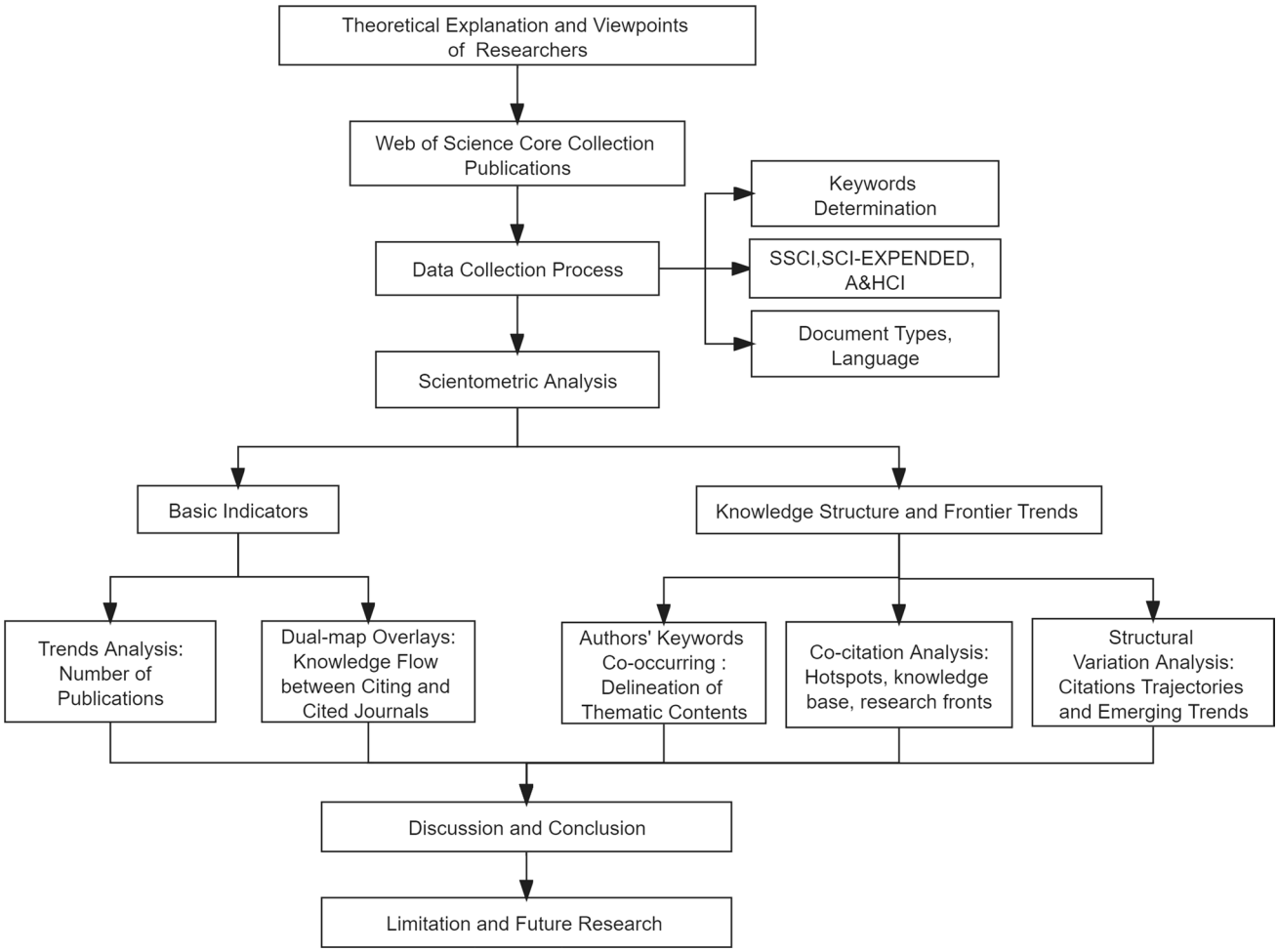

Fig. 1 Workflow of research design

more efficacy and clarity [30]. Also, it offers comprehensive analyses based on bibliographic information, from identifying major research groups to predicting the emerging trends of the selected research domains [20], which is suitable for this research. This study primarily focuses on the following analyses:

- Annual publication analysis with article fitting curve
- Keywords co-occurring analysis focused on major topics
- Reference co-citation analysis for influential articles and emerging trend

3 Results

3.1 Trends of publication

Overall, publication trends in sustainable higher education revealed an exponential increase, as shown in Fig. 2. So far, 5370 research articles and reviews have been indexed in the database. The research output increased from 148 in 2010 to 980 in 2022. The vertical axis on the left is devoted to the number of publications per year. In contrast, the vertical axis on the right represents the accumulated number of publications that contributed to the research domain. Moreover, the blue trend line demonstrates the accumulated number of publications. The equation is obtained by fitting curve analysis, which indicates that the exponential fitting (displayed in red dashed line) is of optimal prediction effect, with $R^2 = 0.96914$. According to Hair et al. [37], the R^2 ranges from 0 to 1 with three threshold values; 0.75 is substantial, 0.5 is moderate, and 0.25 is weak. This exponential fitting coefficient shows substantial predictive power.

Table 1 Search queries with a timespan between January 01, 2010, and December 31, 2022

Set	Results	Query construction	Database
#1	5,722,155	"IT" (Topic) OR "information technology" (Topic) AND Article or Review (Documents types) AND English (Language)	WoS Core Collection (SSCI, SCI-EXPENDED, and A&HCI)
#2	15,051	sustainab* higher education (Topic) OR sustainab* universit* (Topic) AND Article or Review (Documents types) AND English (Language)	
#3	5370	#1 AND #2	

Table 2 Parameter setting

Parameter	Keywords co-occurring analysis	Reference co-citation analysis
Time Slicing	January 2010 to December 2022	January 2010 to December 2022
Year per Slice	1	1
Node Type	Keywords	References
Criteria: g-index with Scale Factor *K*	*K* = 5	*K* = 5
Pruning	Pathfinder; Pruning the merged network	Pathfinder; Pruning the merged network
Others	Default	Default

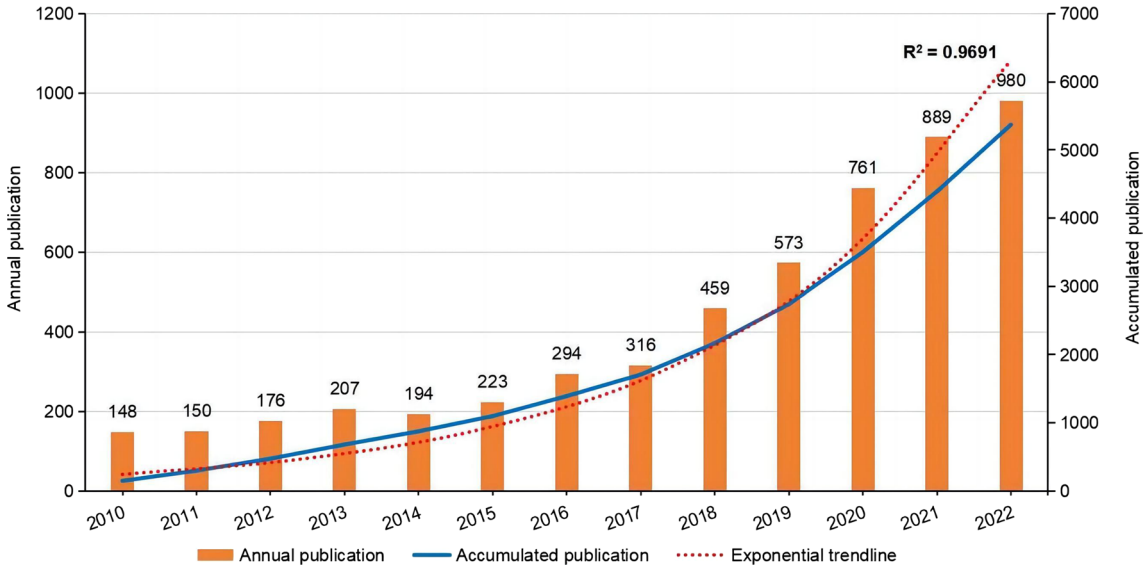

Fig. 2 Distribution of the bibliographic records

3.2 Dual-map overlays

By examining the relationship and direction of knowledge dissemination in the research region, dual-map overlays clearly and intuitively depict the relationship between citations and the knowledge flow process between various publications [33].

Chen and Leydesdorff [38] define that a dual-map overlay of the science mapping literature represents the entire dataset in the context of a global map of science generated from over 10,000 journals indexed in the Web of Science.

The interface displays the base map of citing journals on the left, representing the main subject areas (research front). The base map of cited journals on the right represents the main cited subjects (important knowledge bases) in that research area. The links depict the relationship between the citing and cited journals with Z-scores criteria (Fig. 3). Table 3 explicitly explains the relationships between major citing and cited journals.

Nine distinctive citation trajectories with solid links can be detected, three in yellow, one in green, two in dark blue, and three in blue. The research fronts of the domain mainly concentrated on 2# Medicine, Medical, Clinical, 6# Psychology, Education, Health, 7# Veterinary, Animal, Science, and 10# Economics, Economic, Political.

Publications in the domain are built on top of eight major disciplines on the right-hand side of the map with ellipse circles, namely, 1# Systems, Computing, Computer, 2# Environmental, Toxicology, Nutrition, 4# Chemistry, Materials, Physics, 5# Health, Nursing, Medicine, 7# Psychology, Education, Social, 8# Molecular, Biology, Genetics, 10# Plant, Ecology, Zoology, and 12# Economics, Economic, Political. Among them, the predominant knowledge-based disciplines include 2#, 5#, 7#, and 12#.

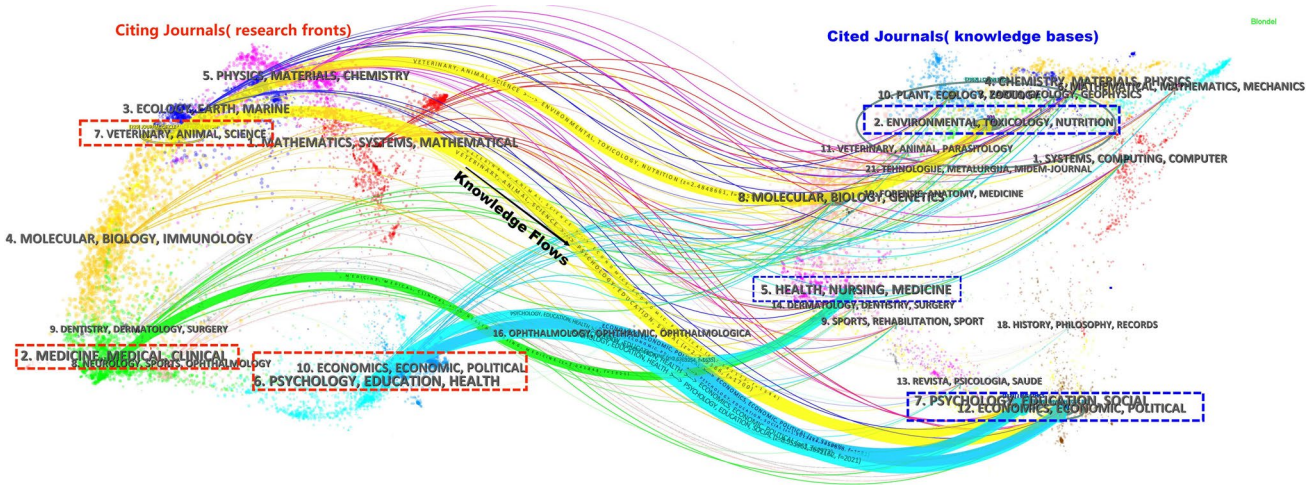

Fig. 3 Dual-map overlay graph

Table 3 Relationships of major citing and cited journals

Citing journals	Major cited journals (4 Largest categories)			
Disciplines	2# Environmental, toxicology, nutrition	5# Health, Nursing, Medicine	7# Psychology, education, social	12# Economics, economic, political
2# Medicine, medical, clinical		√		
6# Psychology, education, health		√	√	√
7# Veterinary, animal, science	√		√	√
10# Economics, economic, political			√	√

3.3 Keywords co-occurring analysis

The following landscape view (Fig. 4) and timeline view (Fig. 5) are based on authors' keywords generated by the top 50 per 1 year slice between 2010 and 2022. The network has a modularity of 0.7506 and an average silhouette score of 0.8917, which are considered very high, since both values tend to be close to 1 [39], suggesting that the specialties in sustainable higher education are clearly defined in terms of keywords co-occurance. Although CiteSpace supports three algorithms to extract cluster labels based on Latent Semantic Indexing (LSI), Log-Likelihood Ratio Test (LLR), and Mutual Information (MI) from citing articles' titles and abstracts [40], LLR is designed as a default algorithm, which tends to reflect the broader range of topics and unique aspects of different clusters [29, 40]. In the following discussion, the research will only focus on significant clusters and intense citation bursts since smaller clusters or bursts are less representative than bigger ones formed by a large number of articles. Table 4 lists the ten major keyword clusters from large to small. In Sect. 3.3.3, the detailed interpretation of each cluster will mainly focus on the five most significant clusters in Table 4 since they are more representative than smaller clusters.

3.3.1 Landscape view

Figure 4 depicts the landscape overview of keywords co-occurring networks. Each research article typically includes a number of keywords represented as nodes in the network. Retrieved from the citing article's "Author Keywords" and "Keyword Plus" fields, each node is depicted with keyword tree-rings across the series of time slices [39].The size of a node indicates how many times that keyword has been extracted from the whole dataset [41]. Algorithmically generated cluster labels identify the nature of a cluster of co-occurring keywords, numbering from #0 Responsible Management Education onwards. The largest cluster #0 Responsible Management Education, is shown in red on the bottom right of

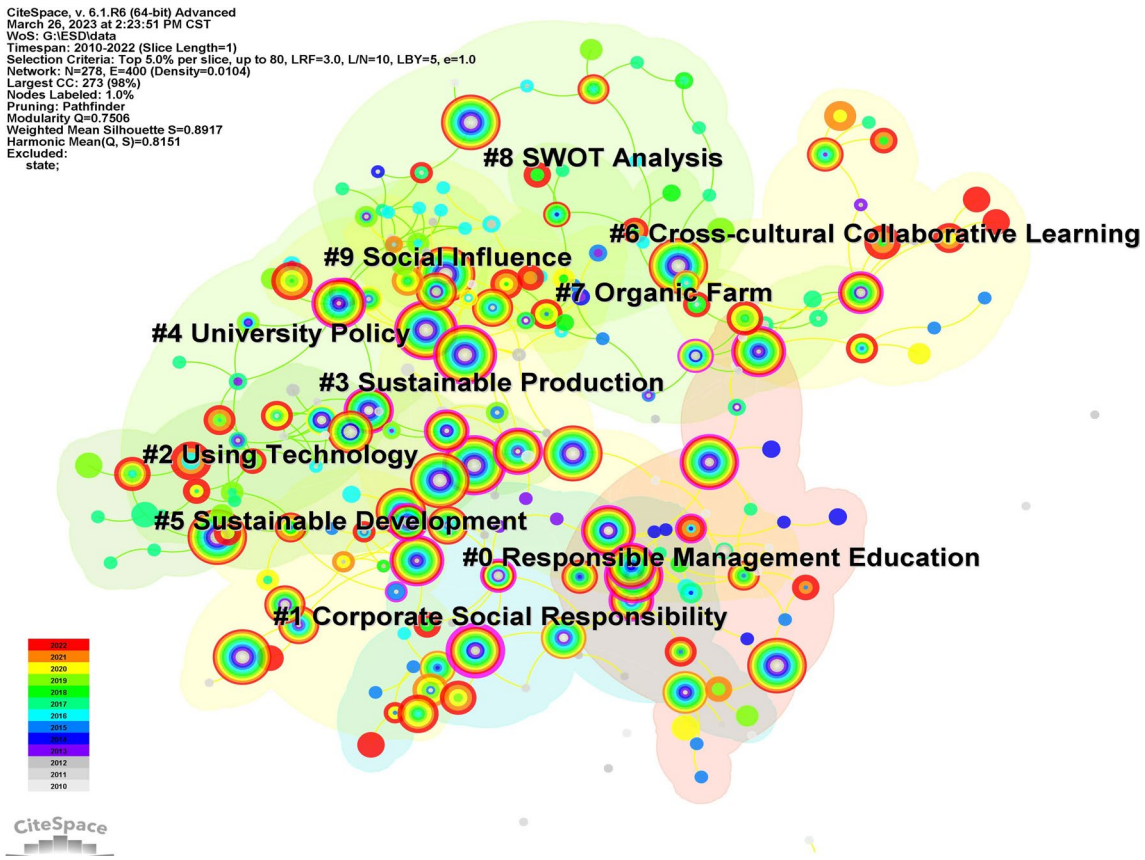

Fig. 4 A landscape view of major 10 keywords clusters

the network. The second largest cluster #1 Corporate Social Responsibility, is displayed in blue on the bottom next to cluster #0. Clusters #2 Using Technology, #3 Sustainable Production, #4 University Policy, #5 Sustainable Development, #6 Cross-cultural Collaborative Learning, #7 Organic Farm, #8 SWOT Analysis, and #9 Social Influence are shown in other distinguished colors.

Various metrics or criteria can be applied to distinguish the importance of terms, for instance, citation frequency [39], betweenness centrality [42], or citation burst [41]. The following discussion will focus on high-frequency keywords.

As depicted in Table 5, the phrases/words "Higher Education Institution", "Education for Sustainable Development", "Sustainable Development", "University Sustainability", "Sustainability Education", and "Management Education" are detected. These high-impact keywords concentrated on 5 clusters, including clusters # 0, # 2, # 3, # 5, and # 12. In particular, the first-placed keywords "Higher Education Institution" (760 counts), as well as "University Sustainability" (366 counts), all belong to cluster # 12 Education Institution.

In this cluster, the major citing article belongs to [43]. This article provided an overview of the contributions of the Asia–Pacific region in promoting sustainability in higher education. The contributions from the Asia–Pacific area highlight the need to utilize the national policy, create regional initiatives, and work collaboratively towards more significant change in higher education through partnerships with external groups and stakeholders.

3.3.2 Timeline view

Figure 5 depicts a timeline visualization of how the network is divided into keywords co-occurring clusters. The sustainability of the cluster varies. Clusters #1 Corporate Social Responsibility, and #5 Sustainable Development sustained the most extended timespan from 2010 to 2022 (13 years).

Other clusters with a relatively long timespan are cluster #3 Sustainable Production from 2010 to 2021 (12 years) with high impact keywords, namely, "Sustainability Education", "University Student", "Knowledge"; as well as cluster #6

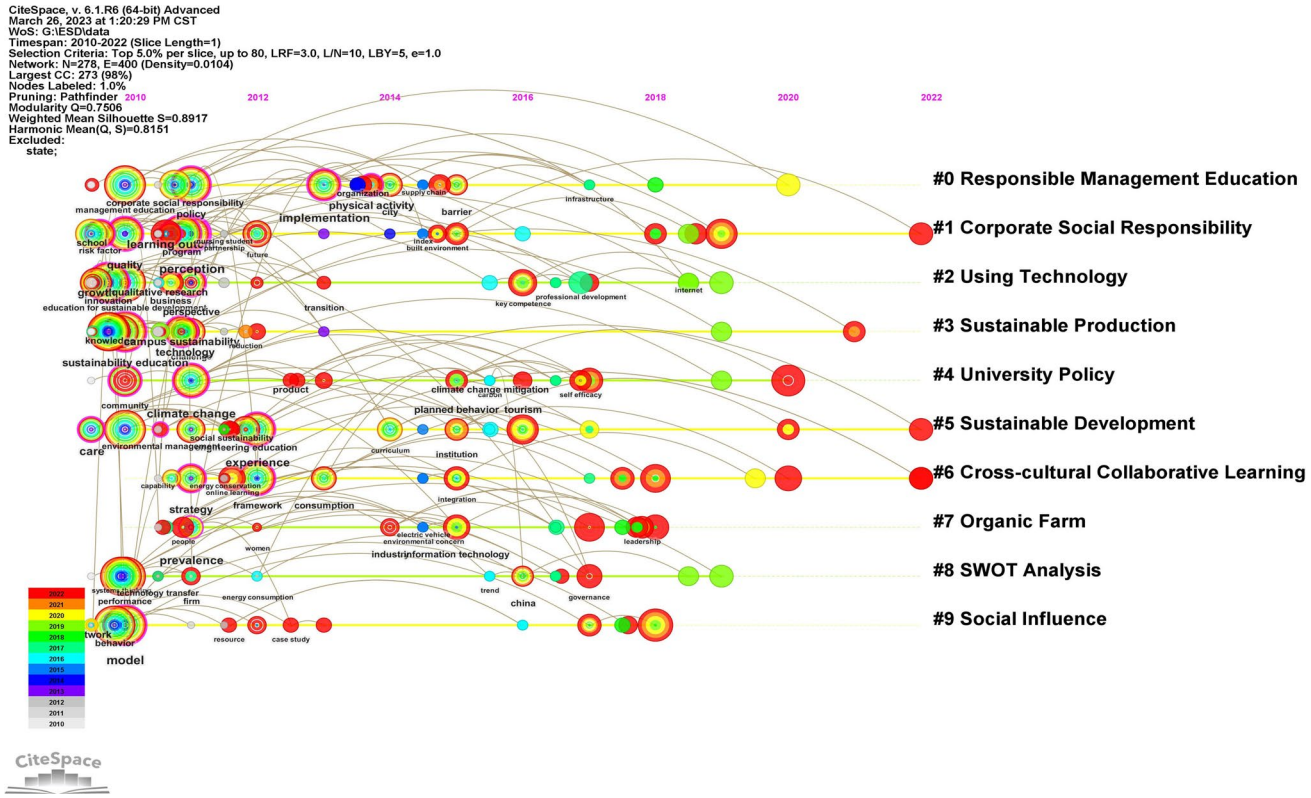

Fig. 5 A timeline visualization of major 10 keywords clusters design

Table 4 Details of major 10 keywords clusters

Cluster ID	Size	Silhouette	Label (LLR)	Year average
0	25	0.861	Responsible management education (635.86, 1.0E-4)	2013
1	25	0.797	Corporate social responsibility (589.61, 1.0E-4)	2013
2	24	0.917	Using technology (746.69, 1.0E-4)	2013
3	24	0.956	Sustainable production (967.58, 1.0E-4)	2011
4	20	0.893	University policy (388.24, 1.0E-4)	2015
5	19	0.924	Sustainable development (1439.54, 1.0E-4)	2013
6	18	0.88	Cross-cultural collaborative learning (467.72, 1.0E-4)	2015
7	18	0.774	Organic farm (416.34, 1.0E-4)	2014
8	18	0.924	SWOT analysis (745.22, 1.0E-4)	2014
9	16	0.834	Social influence (596.15, 1.0E-4)	2013

LLR = log-likelihood ratio algorithm

Table 5 List of the top 6 keywords with high frequency

Rank	Frequency	Keywords	Cluster
1	760	Higher education institution	#12
2	491	Education for sustainable development	#2
3	470	Sustainable development	#5
4	366	University sustainability	#12
5	366	Sustainability education	#3
6	361	Management education	#0

Cross-cultural Collaborative Learning from 2011 to 2022 (12 years) with "Framework", "Consumption", and "Strategy"; while as cluster #0 Responsible Management Education and cluster #4 University Policy both from 2010 to 2020 (11 years). Moreover, clusters #1, #5, and #6 sustained more extended periods than others and had current citation bursts indicating a high potential for continuance attention from academia. The remaining clusters sustained a relatively shorter timespan and gradually faded out.

3.3.3 Keywords cluster interpretation

The following discussion will mainly focus on clusters #0 to #4 since these clusters either sustained longer periods, ended with citation burst nodes indicating the intensive degree of attention, or included more publications or high-frequency cited keywords in the research domain.

In cluster #0 Responsible Management Education, the major citing article by Kalsoom and Khanam [44] employed empirical investigations to enhance the sustainability consciousness of the teachers. Transformative learning experiences can enhance educators' and learners' sustainability consciousness, eventually affecting their behaviors. Other highly influential keywords include "Management Education," which appeared in 361 publications, "Policy," in 120 publications, and "Implementation" in 96 publications.

In cluster #1 Corporate Social Responsibility. Corporate Social Responsibility refers to a company's commitment to its stakeholders and society, including environmental protection and social ethics [45]. It can also be applied in higher education, as the university is responsible for cultivating talents with well-trained professional skills, sustainable lifelong learning competencies, and increased sustainability awareness [46, 47]. The most citing article belongs to Albareda Tiana et al. [48]. To assess the level of competence in sustainability among university students, a well-designed estimating instrument designed by experienced lecturers was applied at the undergraduate and postgraduate levels in the Spanish university system. Furthermore, the most cited keywords include "Perception" and "Quality", with the former appearing in 134 citing papers and the latter appearing in 98 citing papers. ITs are essential for successful implementation in higher education institutions. They allow educators to collect students' feedback, manage learning activity data, analyze the learning outcomes of their course and teaching pedagogy or methodologies more effectively, and develop innovative initiatives for engaging students.

In cluster #2 Using Technology, the most citing article belongs to Tominaga et al. [49]. This essay intends to analyze Brazilian higher education institutions' supply chain management courses focusing on sustainability in engineering education. Additionally, the high-frequency keywords include "Education for Sustainable Development" with 491 counts, and "Innovation" with 243 counts. Collectively, higher education institutions apply innovative and cutting-edge technologies, such as e-learning platforms, digital media, MOOCs, and video conferencing systems, to make learning more adaptive, practical, and student-centered.

In cluster #3 Sustainable Production, Lazzarini et al. [50] analyzed the characteristics of academics engaged in the change process toward sustainable development. It is emphasized that academics' dedication can improve a cultural shift and more profound changes toward sustainable development at the university. The high-frequency keywords include "Sustainability Education" with 366 counts, and "University Student" with 322 counts.

In cluster #4 University Policy, Alghazi et al. [51] examined 127 articles about users' satisfaction with mobile phones as learning tools. This review revealed that many classic research models (TAM, UTAUT) had been extended by adding other factors, such as trust, pre-usage, or attitude. Other highly influential keywords include "Change" with 191 counts and "Community" with 40 counts. In summary, the quality and effectiveness of the curriculum and university management can be evaluated based on students' satisfaction levels. These measurements can uncover weaknesses and promote policy adjustments to meet student expectations better.

3.4 Keywords citation bursts

Citation bursts can identify keywords as indicators of emerging trends in one scientific community [41]. Table 6 shows the top 15 keywords with the most robust citation bursts. The following discussion will be concentrated on:

- The ones with the strongest burst in the group of keywords that ended in the same year
- The ones still active in 2022 with a relatively high potential in predicting future research orientation and emerging trends

Table 6 Top 15 keywords with the strongest citation bursts

References	Year	Strength	Begin	End	2010–2022
Sustainable development	2010	16.37	2010	2012	
Engineering education	2012	5.85	2012	2015	
Developing country	2010	7.57	2010	2017	
Medical education	2012	6.03	2012	2017	
Organization	2014	6.7	2014	2017	
Sustainable development goals (SDGs)	2017	12.9	2020	2022	
Food system	2020	7.39	2020	2022	
Intention	2020	6.71	2020	2022	
Consumer	2020	6.28	2020	2022	
Context	2012	6	2020	2022	
Waste management	2015	6.98	2021	2022	
Satisfaction	2018	6.89	2021	2022	
Bibliometric analysis	2021	6.47	2021	2022	
Stress	2021	6.47	2021	2022	
Online learning	2012	6.33	2021	2022	

The first-placed keyword, "Sustainable Development" exhibits a citation burst from 2010 to 2012, with the highest strength of 16.37. Additionally, the second-placed keyword, "Engineering Education" shows a citation burst from 2012 to 2015, with a strength of 5.85. Both of these belong to cluster #5 Sustainable Development. The high-profile publications include Estrada-Vidal et al. [52] as the major citing paper in that cluster, while Lozano et al. [53] with 381 global citation counts in the WoS. The former discussed the value of sustainable development in society, how attitudes and behaviors affect growth, and the distinctions between personal and corporate responsibility. The latter conducted a worldwide survey to assess the implementation of sustainable development-related declarations, charters, and other initiatives at academic institutions.

The third group ended in 2017, which comprised 3 keywords, "Developing Country" with the highest strength of 7.57. The keyword belongs to cluster #2 Using Technology, which appeared in 29 records and started the burst in 2010. During that period, improving the quality of higher education in developing countries gained significant attention in the academic field. For example, Levy and Schady [54] examined factors influencing sustainable development competencies at Cairo University. Elmassah et al. [55] analyzed Latin America's increased focus on education and social insurance policies.

The fourth group ended up in 2022, which comprised 10 keywords, "Sustainable Development Goals (SDGs)" with the highest strength of 12.9. The keyword belongs to cluster #14 Sustainable Environmental Education, which appeared in 151 records and started the burst in 2020. In cluster #14, the influential publications include Wright et al. [56], which focus on cultivating a collaborative culture for ensuring SDGs and discussing practicable inputs for SDG-related teacher education programs by Almazroa et al. [57].

Another notable keyword is "Online Learning," with a strength of 6.33, the most extended duration from 2012 and the latest burst year in 2021. The keyword belongs to cluster #6 Cross-cultural Collaborative Learning, which appeared in 41 records and started the burst in 2020. Lifintsev and Wellbrock [58] investigated how digitization has affected the way of intercultural communication. The findings revealed that Millennials and Generation "Z" are particularly interested in cross-cultural communication and consider digitalization facilitating communication. Tominaga et al. [49] analyzed the engineering education focused on sustainability in supply chain management and courses. Another impactful research applied "the transtheoretical model" to provide a framework for examining how people make progress toward adopting Sustainable Transport in two universities [59]. To sum up, the application of information technology facilitates cross-cultural interactions. Remote communication software, multilingual websites, and virtual reality simulations provide students with immersive and engaging learning experiences, allowing students from various backgrounds to share

information, interests, ideas, and resources, increase collaboration and efficiency, and reduce misunderstandings between different cultural backgrounds.

3.5 Co-citation analysis

3.5.1 Landscape view

The following landscape view (Fig. 6) and timeline view (Fig. 7) show the overview of a network based on reference co-citation generated by the top 20 per 1 year slice between 2010 and 2022. The network contains 234 nodes (reference) cited, divided into 12 clusters. Table 7 lists ten major clusters by size since large clusters are more likely to be produced by the citation patterns of a significant publication, making them more representative than small clusters [39]. The silhouette score of a cluster, a measure of its homogeneity or consistency, also provides insight into its quality. All clusters in Table 7 are highly homogeneous, with silhouette scores of 0.9321.

Table 8 lists 5 major cited references in the dataset. The most cited article is by Lozano, Lukman, et al. [60], with 139 citations from cluster #2, followed by their research team's other landmark articles [53], which can be regarded as an extension of the previous research, with 119 citations in the same cluster. These two articles focused on commitment and implementing sustainable development in higher education. The former explained the importance of applying sustainable development in higher education. After two years, the research team conducted a worldwide survey to assess the implementation of related declarations.

The third one is a review article by Wiek et al. [61], which identifies the pertinent literature on key competencies in sustainability. It combines the essential contributions into a cohesive framework of sustainability research. Articles at the fourth and fifth positions are all from cluster # 8, namely Wals [62] and Lozano et al. [63]. It can be seen from the above analysis that, with three high-citation articles, Lozano's research team plays a crucial role in the related research area.

3.5.2 Timeline view

Figure 7 depicts a timeline visualization of how the network is divided into distinct co-citation clusters. The legend above the display area marks every 2 years. The duration of a specialty varies.

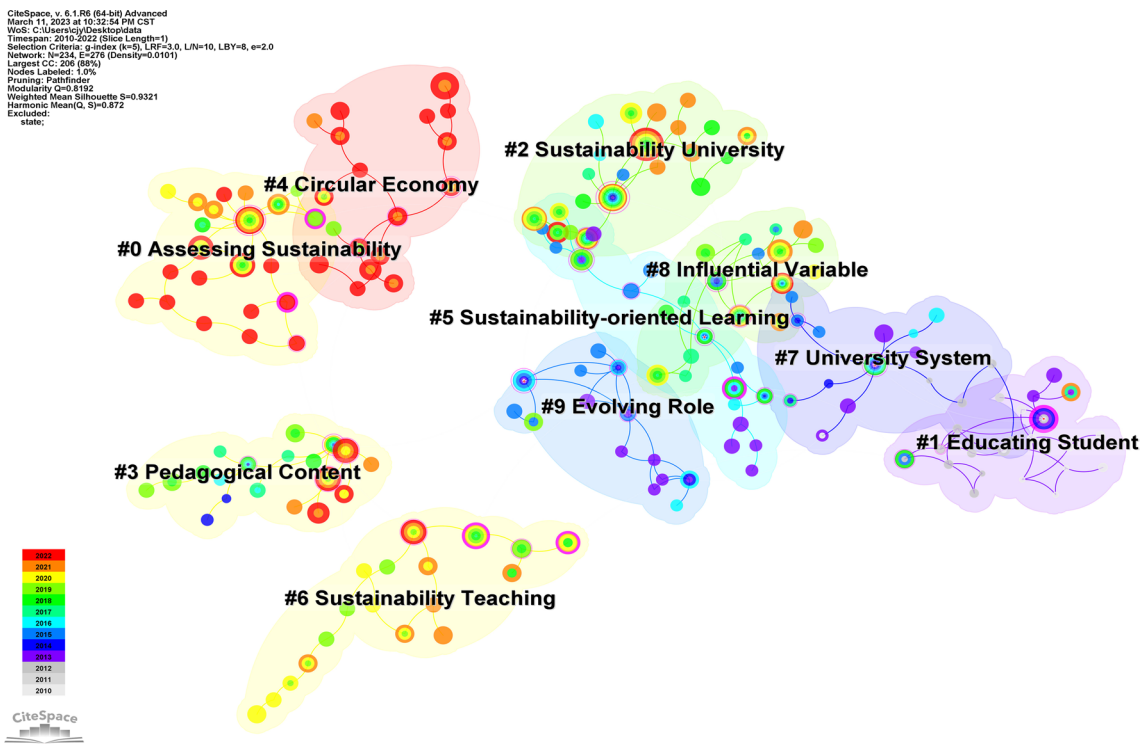

Fig. 6 A landscape view of co-citation network of largest 10 clusters

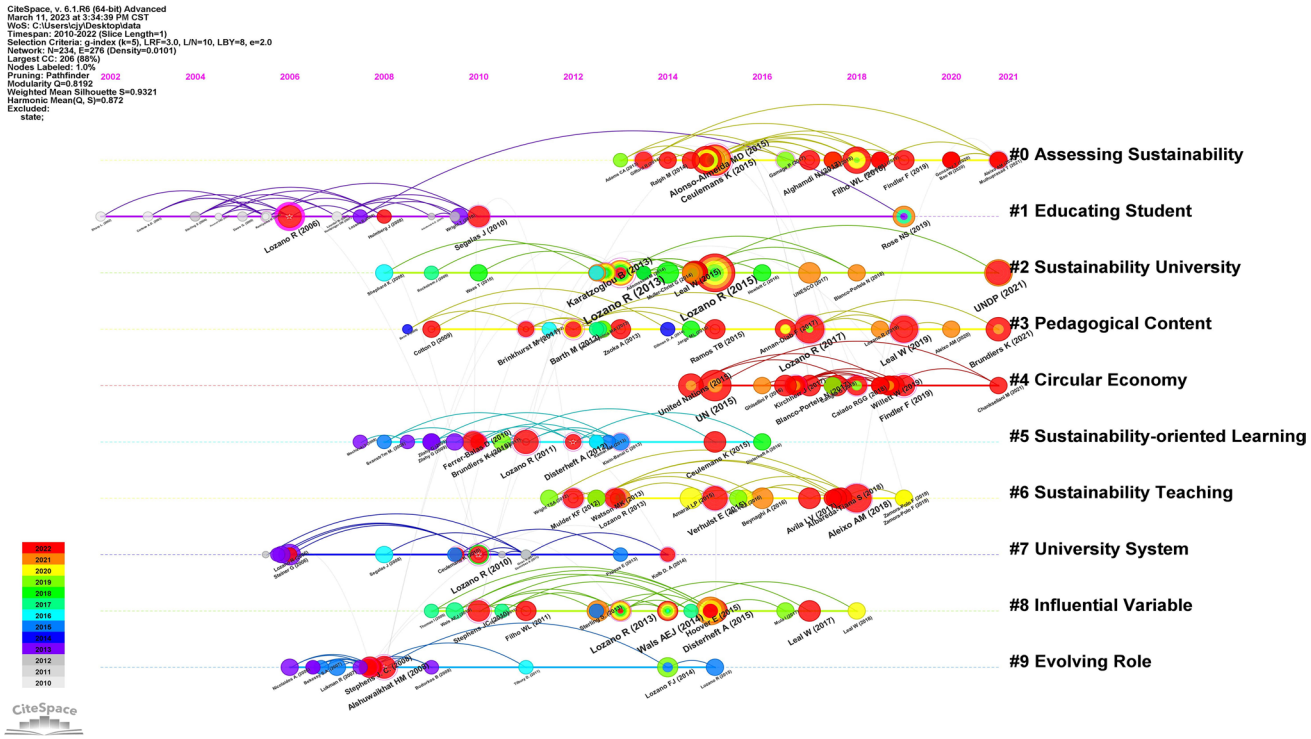

Fig. 7 A timeline visualization of the largest 10 clusters

Table 7 Lists of 10 major clusters by co-citations

Cluster ID	Size	Silhouette	Label (LLR)	Year average
0	22	0.922	Assessing sustainability	2017
1	21	0.916	Educating student	2007
2	20	0.961	Sustainability university	2014
3	19	0.919	Pedagogical content	2014
4	18	0.95	Circular economy	2017
5	18	0.909	Sustainability-oriented learning	2011
6	8	1	Sustainability teaching	2015
7	16	0.848	University system	2009
8	16	0.943	Influential variable	2013
9	14	0.986	Evolving role	2008

LLR log-likelihood ratio algorithm

Cluster #1 has the most extended 18 years timespan from 2002 to 2019, including the earliest citation paper by Sharp [64]. While cluster #4 has the shortest 7 years timespan from 2015 to 2021. However, it is worth noting that cluster #4 displays a high concentration of citation burst nodes, which echoes that this is the most recently developed cluster. Other clusters with a relatively long timespan are cluster #2 (14 years) and cluster #3 (13 years); they are also still active. Cluster #8 and cluster #9 both sustained 10 years, while cluster #5 and cluster #7 sustained 9 years. Although cluster #6 has only 8 years of duration, it contains four high centrality publications with a purple ring outside the node. For instance, Aleixo et al. [65] applied a qualitative approach to explore how the main stakeholders of Portuguese Public Higher Education Institutions perceive the concept of sustainable development and how to overcome the barriers and challenges for long-term sustainability in the higher education area. Similarly, from the perspective of organizational change management, Verhulst and Lambrechts [66] presented a conceptual

Table 8 Top 5 cited citations

Counts	Author	Title	Cluster
139	Lozano, Lukman, et al. [60]	Declarations for sustainability in higher education: becoming better leaders, through addressing the university system	# 2
119	Lozano et al. [53]	A review of commitment and implementation of sustainable development in higher education: results from a worldwide survey	
78	Wiek et al. [61]	Key competencies in sustainability: a reference framework for academic program development	# 10
64	Wals [62]	Sustainability in higher education in the context of the UN DESD: a review of learning and institutionalization processes	# 8
56	Lozano et al. [63]	Advancing Higher Education for Sustainable Development: global insights and critical reflections	

model which links human factors to the sustainable development integration process. It highlights the importance of continuously supporting sustainable development integration in higher education.

3.5.3 Cluster interpretation

In this section, the study will mainly focus on the top 4 clusters since they are more representative than small clusters.

Cluster #0 Assessing Sustainability is the largest cluster, containing 22 members and a silhouette value of 0.922. The median year of all references is 2017, indicating this cluster with a recently formed intellectual base. The most representative citing paper is by Kapitulčinová et al. [67]. This study introduced an "Accelerator" toolset for integrating sustainability principles in higher education and the tools, methods, frameworks or models, and approaches for sustainability integration. This toolkit has not received enough attention in academic writing despite being used in higher education for over ten years. The high-impact cited papers by Ceulemans et al. [68] provided a comprehensive review of the existing literature on sustainability reporting in higher education, emphasizing the importance of university stakeholders' engagement processes and unified standards for reporting indicators. Similarly, Alonso-Almeida et al. [69] revealed that despite the increasing concerns about sustainable relationship in higher education, the overall development is still in the early stage. Collectively, the main focus in this cluster primarily concentrated on improving the diffusion of sustainability reporting in universities [70], which will benefit not only the students but also the stakeholders and universities.

Cluster #1 Educating Student comprised 21 members with a silhouette value of 0. 916. The median year of all references in this cluster is 2007. Many scholars have focused on applying information technology to improve learners' sustainable learning competency, empowering university students to acquire knowledge in a dynamic environment. Segalàs et al. [71] emphasized that when educating university students, especially in technological universities, increased focus should be placed on treating information technology as a powerful and effective solution to social and environmental problems for society.

By employing quantitative and qualitative indicators for assessment, Pérez-Foguet et al. [72] confirmed that online training courses could be a valuable strategy for advancing the professional development of academics in engineering degrees. In conclusion, academics showed a strong interest in analyzing and evaluating the profound influence of information technology on college students' capacity for transformative thinking and the co-creation of new knowledge [1].

Cluster #2 Sustainability University comprised 20 members with a silhouette value of 0.961. The median year of all references in this cluster is 2014. In this cluster, discussion and research primarily concentrated on sufficiently integrating the concept of transformation in higher education institutions. At the same time, develop collaborative approaches to a better sustainable future from university educators or high education management perspective. For instance, the highly cited publication by Karatzoglou [73] reviewed that due to the multifaceted nature of sustainable development, universities are now essential partners in all pertinent initiatives, working consistently in close coordination with other local partners. In addition, Lozano, Lukman, et al. [60] highlighted that university leaders and educators are powerful change agents whose sufficient involvement and competencies are essential for adjusting and improving processes that enhance educational institutions toward sustainability.

Cluster #3 Pedagogical Content comprised 18 members with a silhouette value of 0.919. The median year of all references in this cluster is 2014. In this cluster, the significant changes in pedagogical paradigms, content, and forms in the digital age have drawn much attention from academics. The high-impact reference by Lozano et al. [74] scrutinizes twelve competencies and pedagogical approaches in a framework based on discovered in the literature. By stressing the relationships between educational techniques and competencies in a matrix form, the framework links the course objectives to delivery in higher education. Another one by Leal Filho et al. [75] researched how to integrate Sustainable Development Goals into university activities, particularly sustainability teaching, using updated technology and proposed implementation plans. To sum up, in the field of higher education, digital instruction is prevalent. Education has shifted its focus from predominantly "teacher-centered" to mainly being "student-centered" Moreover, as the education process becomes more digitalized and dynamic, learning and educating are becoming increasingly collaborative.

3.6 References citation bursts

Major milestones in the sustainable development of higher education can be identified from the list of references with strong citation bursts between 2010 and 2022. A spike in citations suggests that the underlying contribution has received special attention from or is now receiving that attention from the scientific community [39].

Table 9 Top 10 References with the strongest citation bursts

References	Year	Strength	Begin	End	2010–2022
An integrated approach to achieving campus sustainability: assessment of the current campus environmental management practices [76]	2008	14.59	2011	2016	
Higher education as a change agent for sustainability in different cultures and contexts [77]	2008	10.26	2013	2016	
Diffusion of sustainable development in universities' curricula: an empirical example from Cardiff University [78]	2010	12.89	2012	2017	
Key competencies in sustainability: a reference framework for academic program development [61]	2011	19.83	2014	2019	
Future-oriented higher education: Which key competencies should be fostered through university teaching and learning? [79]	2012	9.84	2019	2020	
The integration of competences for sustainable development in higher education: an analysis of bachelor programs in management [80]	2013	9.27	2019	2020	
Education for Sustainable Development Goals: learning objectives [3]	2017	13.06	2019	2022	
Sustainable Development Goals and sustainability teaching at universities: Falling behind or getting ahead of the pack? [75]	2019	10.76	2020	2022	
Transforming our World: The 2030 Agenda for Sustainable Development [22]	*2015*	20.52	2021	2022	
Key competencies in sustainability in higher education—toward an agreed-upon reference framework [81]	2021	9.53	2021	2022	

The 10 cited references with the highest citation spikes across the dataset from 2010 to 2022 are listed in Table 9. The following discussions will focus on the 6 articles with the strongest burst in the group that ended simultaneously.

From 2011 to 2016, the strongest burst is associated with a paper by Alshuwaikhat and Abubakar [76] with a value of 14.59, belonging to cluster #9 Evolving Role, which proposed a framework for a more effective method of achieving campus sustainability to overcome the limitations of the current environmental management procedures in universities through the integration of three strategies. Most publications in this cluster predominately concentrated on proposing holistic approaches [82], programs [48], and models [83] for improving students' competences. Karatzoglou [73] also reviewed universities' evolving roles and contributions to achieving sustainable development or even transformative sustainability [84].

The research by Lozano [78] led to the highest citation burst sustained over six years (from 2012 to 2017), belonging to cluster #7 University System, with a value of 12.89. Using Cardiff University as an example, the study examined the adoption and diffusion of the SD concept in the curriculum. The results showed that although some disciplines had made progress in promoting the related area, challenges still impeded profound in-depth development. Integrating the concept of SD within and across the various disciplines could improve universities in developing a more balanced, synergistic, transdisciplinary, and holistic academic system, enabling graduates to make more significant contributions to the sustainability of societies.

Among citation bursts that ended in 2019, the strongest burst was led by Wiek et al. [61], with a value of 19.83, belonging to cluster #10 Sustainable Science. This literature-based study on critical competencies of sustainability reflects the growing interest in creating a set of convergent competencies that can enhance the integration of sustainability-related programs and courses in science, such as natural sciences, social sciences, and humanities. In the same vein, the representative publications in this cluster also focused on developing joint educational programs [85] and competency-oriented education courses [86].

The next highly impactful article is by Rieckmann [79]. From 2019 to 2020, it experienced a strength value of 9.84 and belonged to cluster #11 Sustainability Audit. The researchers identified twelve key competencies crucial for sustainable development, which should be fostered through university or other higher education institutions. Other academics have emphasized the need for ongoing evaluation and monitoring methods to guarantee the excellence of programs that enhance students' cross-cutting competencies [22, 61]. Collectively, sustainability audit makes an essential contribution to the implementation and design of instruction.

In the last group, citation bursts for all publications persisted until 2022, implying promising future research trends. The most notable among them is the United Nations' [22] publication, with the highest value of 20.52, and the most recent published research by Brundiers et al. [81], with a value of 9.53. Not surprisingly, as the guidelines proposed by United Nations, the Agenda with the highest value is predictable and reasonable. In another influential literature, based on a complete study of the most frequently cited framework by Wiek et al. [61], the experts added two abilities that students should exercise and cultivate in the future: intrapersonal and implementation competencies. This framework allows higher education practitioners to be more aware of what capabilities they need to train college students and what curriculum they need. The synthesized framework can assist in program formulation, implementation, and assessment of sustainable development worldwide. Consequently, future publications regarding cultivating students' sustainable competencies will probably refer to this new framework as the underlying paradigm.

3.7 Sigma

Three metrics can be applied to detecting the milestone intellectual base: betweenness centrality, citation burst, and Sigma. Betweenness Centrality (BC) represents the shortest paths going through a node, which illustrates the importance of a publication in the knowledge map [29]. Citation burst explains the intensity of the burst and the duration of the burst status [87]. Although BC is the most commonly used indicator to detect pivotal nodes [20, 24], other influential scholars also employ Sigma as a critical metric for analysis, such as Dr. Chaomei Chen [39]. The Sigma measures both structural centrality and citation bursts of a cited reference. This research will concentrate on the publications with relatively high Sigma values since if a reference is strong in both measures, it will have a higher Sigma value than a reference that is only strong in one of the two measures [39].

Figure 8 and Table 10 illustrate structurally six essential references in the synthesized network with the highest Sigma values. These references are critical because they connect not only individual nodes but also aggregated groups of nodes

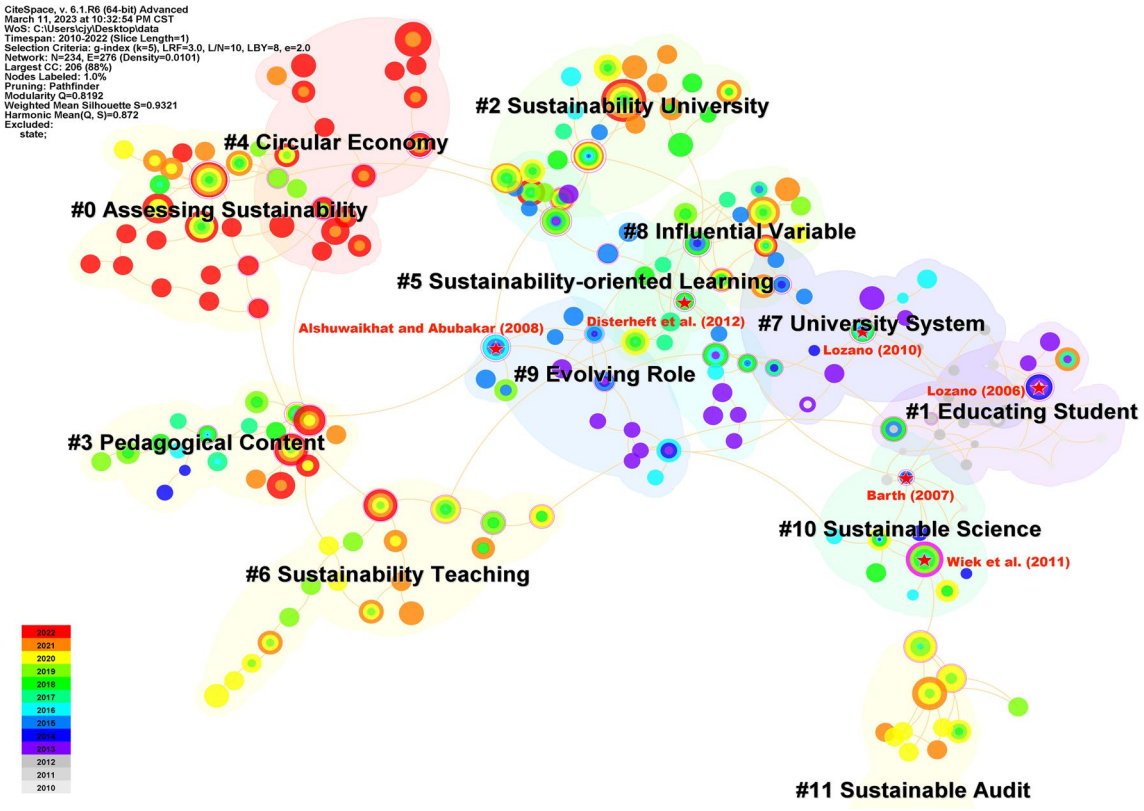

Fig. 8 Top 6 cited citations with highest Sigma

Table 10 Top 6 cited citations with the highest Sigma

Rank	Sigma	References	Cluster	Link clusters	Link type
1	74.17	Lozano [88]	#1	# 7, # 10	Transformative
2	66.81	Lozano [78]	#7	# 1	Transformative
3	49.36	Alshuwaikhat and Abubakar [76]	#9	# 2	Transformative
4	37.52	Wiek et al. [61]	#10	#11	Transformative
5	8.79	Barth [89]	#10	# 1, # 5	Transformative
6	5.9	Disterheft et al. [90]	#5	#5	Incremental

in the network. Two different types of co-occurring links can be detected. The links connect distinct clusters belong to transformative links, whereas within-cluster connections are considered incremental links [87].

With the highest Sigma value, Lozano [88] proposed that trans-disciplinary approaches and strategies should become integral to SD collaboration in higher education institutions. Integrating environmental, social, and ethical visions into the university policy framework is also necessary. This article is one of the impactful foundational works of Lozano's research team, which has published a series of influential studies in the last decade. It made substantial connections among three different clusters, namely clusters #1, #7 and #10, which contributed to a profound impact on the global structure of the underlying research field, as depicted in Fig. 8. The links among these clusters are termed transformative links since they connect distinct clusters rather than connections within the cluster [88].

Lozano [78], Alshuwaikhat and Abubakar [76], and Wiek et al. [61] located not only second-placed, third-placed, and fourth-placed in terms of high Sigma values but also exhibited high citation burst values from 2012 to 2017, 2011 to 2016, and 2014 to 2019, respectively. They connected clusters #1 and #7, #2 and #9, and #10 and #11 with transformative links.

Ranked fifth place, Barth [89] analyzed the effects of innovative approaches for acquiring critical competencies in higher education on both formal and informal learning environments. Additionally, this reference connected three clusters, namely clusters #1, #5, and #10, particularly with Lozano [88] and Wiek et al. [61]. These articles concentrate on assisting students in improving sustainable competencies by integrating information technology and interdisciplinary knowledge, enabling students to have lifelong learning skills with the ethical values of social and environmental sustainability. The results demonstrate the strong connections between these references, opening research fronts based on the three clusters mentioned above.

Disterheft et al. [90] concentrated on implementing Environmental Management Systems in European higher education institutions. The university's management must implement the concept of campus sustainability through Top-down approaches, which impact the daily operations of institutional management and research. Reducing energy consumption and emissions and improving waste management can contribute to developing new behaviors and lifestyle concepts that consider the well-being of current and future generations. Comparatively, it is less representative than others since it mostly connected nodes within cluster #5 in terms of the Sigma value.

3.8 SVA and emerging trends

Extraordinary attention should be focused on articles or thematic concentrations with high transformative potential. Newly published articles can connect scattered nodes or clusters to the research area. However, not all can bring profound and transformative changes to the domain. Whether successfully consolidate, synchronize, or synthesize different areas as brand-new research direction will depend on if the academics follow the promising edges forged by innovative connections [87]. Structural Variation Analysis (SVA) is a predictive analytic process that can be used to identify whether newly published articles have novel variants. Transformative potentials are measured in terms of three harmonic mean of modularity change (M), cluster linkage (C-L), and centrality divergence (C-D) [87]. The modularity of a network is a measure of how clear the network structure is in terms of how well the whole network can be naturally split into different clusters [91]. A recently published article will be considered to possess transformative power to introduce a profound structural variation on the entire structure if it significantly changes the modularity value. Modularity Change evaluates the difference between the previous and newly formed networks [39]. Cluster linkage (C-L) represents connections of co-cited references between clusters. For instance, if an article adds links, it may alter the overall structure [92]. Centrality Divergence (C-D) refers to how the structure of the network in terms of centrality has changed after new articles have been introduced [92]. The harmonic mean synthetically considers the three structural variation indicators. The higher the harmonic mean value is, the greater potential of an article to make drastic changes in the analyzed domains [87].

Table 11 lists the Top 3 citing articles with the highest Harmonic mean displaying high potential for creating new ideas or triggering new research domains. Figure 9 depicts the evolution process by displaying the citation trajectory of each important citing paper separately in Fig. 9a–c and the combined view in Fig. 9d. The red lines display the distribution of the references cited in the article across various clusters.

Veiga Ávila et al. [93] in Fig. 9a, cited different references belonging to clusters #3, #6, and #8, depicting novel co-citation links. The study, which was based on global research, identified barriers to innovation and sustainability in institutions across continents. The findings revealed that lack of planning and focus, lack of environmental concerns, and lack of consistency and applicability of actions in the long term are the main barriers. Universities can overcome and be responsive to existing and emerging sustainability barriers and challenges through innovation in teaching, research, and activities [93].

Dzimińska et al. [94] in Fig. 9b, cited different references belonging to clusters #3, #8, and #11, generating novel links based on these specialties. By proposing a conceptual model, this paper clarifies the role of universities in initiating, promoting, and modeling changes while appreciating the role of culture as an enabler of social change in sustainable development. The foundation that influences all elements of sustainable actions adopted by universities in the daily administration and educational processes are the cognitive levels of the institution's culture and core values. As a foundation and catalyst for knowledge and education, the degree to which the university attaches importance to its social responsibilities significantly impacts the extent to which its learners can integrate their cultural values into social actions to promote a sustainable future.

Leal Filho et al. [95] in Fig. 9c, cited different references belonging to clusters #3, #4, and #11, revealed cross-cluster connections. Through an online international survey, this research evaluates university educators' sustainable teaching competencies and emphasizes four essential sustainable development competencies they should possess: comprehension, implementation,

Table 11 Top 3 articles with the strongest transformative potentials in terms of Harmonic mean

Rank	Harmonic mean	C-D	C-L	M	Title	References
1	2.74	0.82	− 7.5	100	Barriers to innovation and sustainability in universities: an international comparison	Veiga Ávila et al. [93]
2	1.58	0.56	10.12	84.81	A Conceptual Model Proposal: Universities as Culture Change Agents for Sustainable Development	Dzimińska et al. [94]
3	1.27	0.43	65.19	82.91	University teaching staff and sustainable development: an assessment of competences	Leal Filho et al. [95]

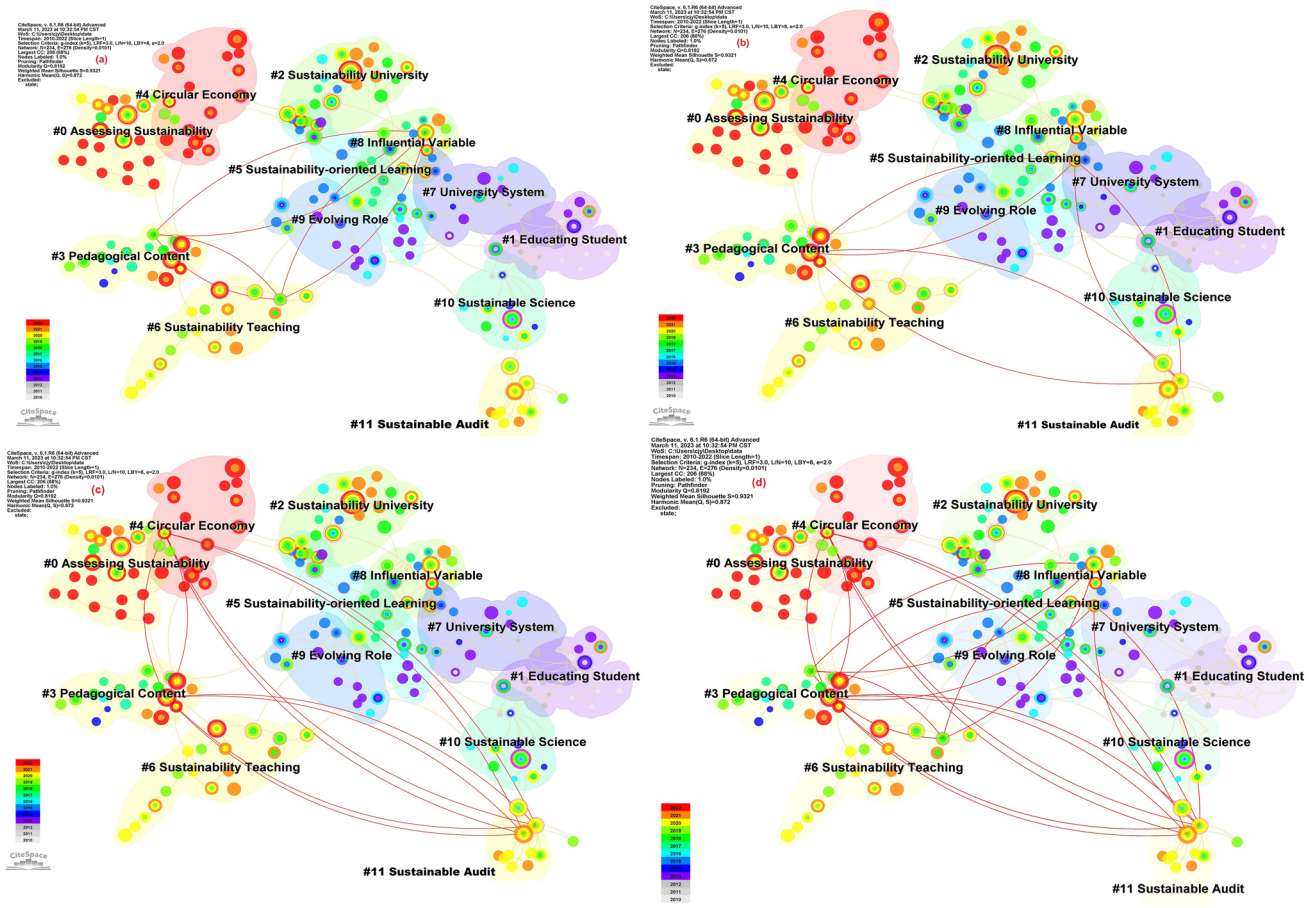

Fig. 9 **a** Veiga Ávila et al. [93], **b** Dzimińska et al. [94], **c** Leal Filho et al. [95], **d** Novel co-citation trajectories of top 3 articles

innovation, and collaboration. Improving educators' sustainable teaching competencies ultimately contributes to learners' sustainable development ability for lifelong learning.

Collectively, it is evident that clusters #3, #4, #6, #8, and #11 drew particular attention from scholars and researchers. All references are cited in different sections or distinct clusters, indicating promising trends for further breakthroughs and other research threads in the science community.

4 Discussion

4.1 Intellectual bases

The present scientometric analysis reveals several essential insights into information technology in sustainable higher education research areas. As an emerging field, the results indicated that academic interest had increased substantially as annual publications exhibited exponential growth between 2010 and 2022. Predictably, this research area will demonstrate strong sustainability as a prevalent academic issue.

Firstly, the most popular research domain is applying cutting-edge information technology in web-based education in today's fast-changing and rapidly evolving environment. Innovative technologies, such as virtual and augmented reality, gamification, and social network, contribute to the profound development of shifting the education process pattern [8] and increase the flexibility and efficiency for learners in acquiring knowledge [1]. The results from keywords co-occurring analysis supported this inference. Regarding keywords citation burst analysis, "Online Learning" is the most recently developed and extensively cited term in academia. Since the evolutionary innovation of information technology has permeated different spheres of life in sector-specific ways, education has no exception [23]. The learning process and tracking performance are increasingly reliant on data-based technologies. Innovative

digital technology assumes the role of facilitator in the learning process and the fuel to drive the progression in the educational sector in an open, dynamic environment [8].

Secondly, in line with SDG4 Quality Education, which advocates for an inclusive and equitable quality education regardless of a student's background, innovative technologies reduced inequality in higher education by making resources more accessible, affordable, and personalized [96]. Students who live in rural or remote places can benefit without physically attending the classrooms, especially in developing countries [97]. For instance, with various resources, MOOCs built on technological innovations require only essential digital experience and skills accessible to any individual, regardless of age, gender, education level, location, or geography [98].

Thirdly, campus sustainability has received significant attention in academia since a large amount of university activities are taking place on campuses, such as educating and supporting services for students and employees, which involve energy consumption and emission of pollutants, and eventually indirectly or directly affect the environment [76]. Extensive studies emphasized that the crucial sustainable vision of the higher education (HE) institution should focus on achieving the lowest feasible levels of energy consumption and pollution emissions during the whole operation process while maintaining the quality of its education.

Finally, the review article utilizing bibliometric analysis bears important academic significance and practical value [99]. Due to the rapid evolution at an exponential pace, an updated synthesized review of the empirical research should be applied to better track intellectual fronts and emerging trends in related fields. "Bibliometric Analysis" exhibited high strength value and contributed to the top 15 keywords citation bursts. Some review articles demonstrate high impactful value in different metric criteria. A review article by Lozano et al. [53] ranked in the top 5 citation list, which reviewed sustainable development in higher education through a worldwide survey.

4.2 Frontier trends

The highest research attention can primarily be concentrated on empowering college students to develop competencies that contribute to sustainable development, including knowledge, skills, values, and attitudes. Especially in complex and dynamic situations nowadays, considering the current and future impacts of what students learn and how they will act from local and global perspectives cannot be less emphasized. An integrated framework regarding students' well-developed competencies should be included. Besides basic academic competency and lifelong learning ability, interpersonal competency and integrated problem-solving competency should also be empowered.

Meanwhile, research should focus on the continuous attempts to constantly alter the curriculum content, course objectives, and pedagogy to achieve the changing socioeconomic and ecological situations and demands on the skills and ethics of future practitioners. Transformative pedagogy that encourages learners to engage in participatory, systemic, and creative thinking and a holistic and comprehensive project-oriented and action-oriented approach should be continuously promoted. Partnerships and communication between learners from different cultural backgrounds can foster synthesized thinking competencies and enhance sustainable development in education. For example, web-based education settings and courses can provide a place to practice a global dialogue and build respect and understanding among people from different backgrounds.

Moreover, integrating sustainability for educators' improvement can be another potential research focus. Educators' competencies are essential for restructuring educational processes and improving educational outcomes toward sustainability [3]. Educators and lecturers must be prepared to foster sustainability competencies and assist learners, especially college students, in developing sustainability competencies through creative and dynamic adjusted teaching. The citation burst analysis and SVA results supported this inference since representative articles in these two analyses by Leal Filho et al. [75] and Leal Filho et al. [95] all concentrated on developing sustainable HE competencies in teachers' education.

In addition, the circular economy (CE) has drawn a lot of interest and will remain a hot topic in the research domain. The results from co-citation support this inference since cluster #4 Circular Economy is the most recently developed cluster, not only with a high concentration of citation burst nodes but also ending with a citation burst. Higher education plays a vital role in promoting the transition to a circular economy. By educating graduates with skills, competencies, and awareness of sustainability goals, the education system can create a favorable environment for this shift towards a more sustainable future [100]. There is increasing focus on researching the benefits of collaborative learning initiatives between academia and industry, particularly through joint modules. Based on a collaboration between higher education institutions and external organizations, these projects allow participants to achieve knowledge through social interactions and develop personal skills (teamwork, responsibility, independence, confidence, and leadership) while actively exerting the function of external organizations' social education [101].

Furthermore, establishing a unified and transparent university sustainable assessment mechanism to evaluate sustainability outcomes in higher education, especially sustainable reporting with all practitioners, such as policy-makers, educators, learners, and stakeholders, can be another arousing research area. The results from the co-citation analysis supported this inference since the largest cluster #0 Assessing Sustainability, concentrated on the related research area of sustainability reporting, putting forward barriers and challenges. Further research should concentrate on more in-depth studies, preferably with empirical evidence.

Nonetheless, despite the excellent IT advancement in sustainable higher education domain, some issued has been raised, such as high dropout rate and low completion after registration. The convenience of the online learning platform enables students even easier to drop out the course if they are unsatisfied with it [102]. Increasing students' learning motivation and ensuring that they complete the course, as opposed to only enrolling in it, is a vital question [103, 104]. Multiple factors, including social [105, 106], psychological [107], and course-related [108], can influence students' perceived satisfaction and eventually affect their completion rate of the course. Consequently, scholars will pay great attention to relevant topics on identifying factors affecting completion rates and determining the measures that can be adopted to reduce the dropout rate of online courses.

5 Conclusion

In conclusion, examining the scholarly literature of IT and sustainable higher education, with dual-map overlay analysis, keyword co-occurring, and reference co-citation, has delineated the evolutionary trajectory of collective knowledge from 2010 to 2022. This scientometric review conducted research using comprehensive bibliographic data derived from WoS to provide quantitative information about the global research field of information technology in higher education. After the rigorous screening process, a sampled literature dataset, including 5370 bibliographic records, was finally selected from WoS Core Collection, fulfilling the inclusion/exclusion criteria.

Firstly, the publication analysis shows that the research on sustainable IT development in higher education has exponentially increased since 2010. Through dual-map overlay analysis, nine distinctive citation trajectories are detected, indicating knowledge flows from cited articles to citing articles in terms of disciplines. The predominant research fronts of citing paper include 2# Medicine, Medical, Clinical, 6# Psychology, Education, Health, 7# Veterinary, Animal, Science, and 10# Economics, Economic, Political, while 2# Environmental, Toxicology, Nutrition, 5# Health, Nursing, Medicine, 7# Psychology, Education, Social, and 12# Economics, Economic, Political comprise the major intellectual bases.

Secondly, leveraging keywords co-occurring, clustering, timeline, and citation burst analysis revealed topics' research hotspots and evolution process. Online learning technology, responsible management in higher education institutions, sustainable production, cross-cultural collaborative learning, and achieving the SDGs of the United Nations comprise the highest impact topics, the major intellectual bases in terms of thematic studies while having a high potential for retaining continuous attention from scholars. The findings indicate that IT is increasingly significant in creating innovative educational approaches. In this sense, it is critical to emphasize that educators should change traditional education in a variety of ways by taking advantage of innovative information technologies, including an intensive focus on e-learning, distance learning, mobile learning, and online learning, and using them to eliminate participation inequalities and the digital divide in society [109, 110]. Information technologies have resulted in attaining the objectives of UNESCO for Sustainable Development, especially in SDG4, to provide quality education, reduce inequalities and differences, and facilitate lifelong learning ability [3].

Thirdly, references co-citation analysis illustrated intellectual bases and research fronts of this research domain. In total, twelve clusters were generated, and five highly influential clusters are cluster #0 Assessing Sustainability, cluster #1 Educating Student, cluster #2 Sustainability University, cluster #3 Pedagogical Content, and cluster #4 Circular Economy. Lozano, Lukman, et al. [60], Lozano et al. [53], and Wiek et al. [61] were the three most-cited citations. Moreover, clusters #0, #2, #3, and #4 exhibited still active with high citation bursts.

In higher education, sustainability efforts should prioritize critical thinking and strive to achieve a balanced economic, social, and environmental relationship for a brighter future. By leveraging information technology to collect learners' feedback and assess course performance with high efficiency, educators and institutions can regularly update their curriculum, course objectives, and teaching methodologies to align with industrial, institutional, social, ecological, and economic changes [111].

Fourthly, through Structural Variation Analysis, the promising topics with high potential that might influence future directions include the following aspects: utilizing information technology to improve students' cross-cultural

communication ability and transformative competencies; ongoing improvement of the curriculum; continuous improvement of educators' ability to reconstruct educational processes for better learning outcomes; and the establishment of instantly updated, transparent, and consistent evaluation standards for sustainable higher education assessment.

Finally, substantial changes in the research field's focus can be summarized. A rising focus on assessing students' digital competencies and incorporating sustainability principles into the teaching–learning process has been noticed, rather than only discussing the use of IT to construct web-based courses or platforms at the early stage. The importance of enhancing educators' awareness of sustainable development and assessing the evaluation system higher education has achieved in that direction is also receiving more emphasis.

6 Limitations and further study

The current study was confined to the English-written articles and reviews in online databases in WoS Core Collection. In more comprehensive database selections, there might also be related academic materials in other article types, such as book chapters, dissertations, and technical reports. It also primarily focused on keywords and reference analyses; however, additional information can be obtained, such as institutional collaboration analysis and authors' collaboration analysis from the micro-perspective.

Nevertheless, this research still lends itself well as a roadmap toward the continuity of information technology in the higher education research area. Because the articles in the core database represent the top academic insights, the applied data search algorithms have successfully eliminated less influential articles in the industry.

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Data availability Not applicable.

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Declarations

Competing interests No competing interests.

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