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Three Decades of Sustainability Research: A Bibliometric Perspective (1996-2025)

Ibtissem Gannoun [1], Majdi Argoubi [2], Khaled Mili [3*], Ismail Bengana [4]

[1] *Department of Economic Sciences and International Trade, University of Sousse,* TUNISIA*; and Member of the Larma Research Laboratory; Email: Tunisia.ibtissemgannoun@gmail.com*
[2] *Department of Quantitative Methods, University of Sousse,* TUNISIA*; Email: mejdiargoubi@yahoo.fr*
[3] *College of Business, King Faisal University,* SAUDI ARABIA*; Email: Kmili@kfu.edu.sa*
[4] *College of Business, King Faisal University,* SAUDI ARABIA*; Email: ibengana@kfu.edu.sa*

***Corresponding Author:** Kmili@kfu.edu.sa

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ABSTRACT

Over the past three decades, research on sustainable development has evolved from a predominantly environmental and economic concern into a broader field encompassing cultural, social, and ethical dimensions of global transformation. This study conducts a bibliometric and scientometric analysis of the sustainable development literature from 1996 to 2025, using data from the Web of Science. By examining publication and citation patterns, identifying key authors, institutions, and countries, and visualizing collaboration networks, the study captures how sustainability has emerged as both a scientific paradigm and a cultural discourse shaped by diverse worldviews and power dynamics. The analysis identifies five major research clusters: (1) Resources, Growth, and Sustainability; (2) Global Sustainability and Trade; (3) FinTech and Resource Management; (4) Urbanization and Natural Resources; and (5) Ecosystem Valuation and Adaptation. These thematic areas illustrate how sustainability research reflects evolving societal narratives about progress, equity, and ecological responsibility.

Our findings reveal increasing interdisciplinarity across environmental science, economics, and political studies, yet underscore the continuing need to integrate cultural analysis and voices from the Global South into global sustainability debates. By mapping the intellectual and social architecture of the field, this article provides a critical reflection on the ways in which knowledge production both mirrors and influences contemporary social change. It offers pathways for more inclusive and culturally grounded research agendas capable of addressing the complex interplay between sustainability, justice, and global transformation.

Keywords: Sustainable Development, Climate Change, Growth, Globalization, Bibliometric Analysis

JEL Classifications: Q01, O44, C80

INTRODUCTION

Sustainability is based on the principle of the renewal of the exploited resource, where the ratio of resource extraction does not exceed its renewal rate. The idea of sustainability, although formalised late with the concept of sustainable development, finds its roots in ancient initiatives and reflections related to natural resource management, ecosystem conservation, and the limits of economic development. The history of sustainability dates back to the Middle Ages with the Ordinance of Brunoy (1346), which already laid the foundations for sustainable forest management, illustrating a linear vision of time and the need to preserve natural resources

(Clément, 2004). This idea was reinforced by the Great Reformation of Forests under Colbert, which reaffirmed the preservation of resources for future generations.

In the 18th century, Thomas Robert Malthus introduced the issue of resource limits in his 'Essay on the Principle of Population' (1798), emphasizing the Earth's inability to feed a growing population (Arnould, 2004; Veyret, 2005). However, his conclusions, which advocated for the elimination of the poorest populations, diverge from the principles of sustainable development (Lefort, 2005).

In the 19th century, the issue of exploitation versus preservation of nature and its resources became increasingly prominent. Henry David Thoreau (1817-1862) and Ralph Waldo Emerson (1803-1882), both important figures of transcendentalism, called for a recommitment to nature, and contributed to the evolution of today's environmental movements (Voisenet, 2005). At the same time, George Perkins Marsh (1864), in "Man and Nature," criticized the waste and ruin of the earth's resources, condemned the disastrous impacts of human alteration of land, and supported a strategy for dealing with natural resources that was more sustainable (Lefort, 2005; Veyret, 2005). Two dominant movements emerged in the U.S.A. at the end of the 19th century; preservationism and conservationism. The former advocated for the total preservation of natural spaces, while the latter argued for the rational exploitation of resources (Vivien, 2001; Arnould, 2004; Veyret, 2005).

Through the lens of sustainability, but following the vision of German geographers Friedrich Ratzel and E. Friedrich, the consequences of the plunder economy necessitate sustainable resource management (Mathieu, 2001; Vivien, 2001; Arnould, 2004). Carl O. Sauer, a leading figure in the Berkeley school of geography, emphasized the importance of a sustainable relationship between societies and their environment (Veyret, 2005).

These discussions led to the first international initiatives – the Berne Conference of 1913 regarding the protection of landscapes and the International Congress regarding the Protection of Flora and Fauna in 1923 (Paulet, 2005). While those initiatives didn't explicitly use the word 'sustainable development,' their work laid the groundwork for today's notions of management of ecological and economic resources. In contemporary history, there are 12 significant dates taken into account in the history of sustainable development, from the earliest thoughts in the 1950s about reconciling economy and ecology to recent international agreements such as the Paris Agreement on climate (2015) and the Kunming-Montreal agreement (2022) on biodiversity. These milestones mark the gradual awareness of the limits of planetary resources and the need to consider social, economic and environmental aspects in development policies. The Sustainable Development Goals (SDGs), which were ratified in 2015, represent a universal framework for guiding action towards a more sustainable, inclusive and equitable future. The term sustainable development, understood simply as the ability of a system to remain in equilibrium, emerged following the awareness in the 1970s of the ecological limits of growth to economy or demographics. At this time humanity recognized its responsibility to the environment and the need to enact preventative policies to protect ecosystems.

The Brundtland Report, 'Our Common Future', published in 1987, significantly catalyzed the discourse on a development paradigm that integrates economic advancement, ecological stewardship, and social equity. Since its release, sustainable development has ascended to a position of paramount importance in governmental and corporate agendas, extending beyond a purely philanthropic approach (Vivien, 2001; Voisenet, 2005; Bartenstein, 2005; Allemand, 2006; Boisvert and Vivien, 2006). This field is inherently interdisciplinary, drawing from a diverse array of disciplines including environmental sciences, economics, sociology, anthropology, public health, and political science. Each of these disciplines contributes unique analytical perspectives to the study of sustainability, yet they are united by a common objective: the harmonization of economic, social, and environmental considerations. For example, economics investigates sustainable growth models, the management of natural resource endowments, and the mitigation of environmental externalities; geography examines patterns of land use and the reciprocal interactions between human societies and ecosystems; environmental sciences and ecology focus on the conservation of biodiversity, the amelioration of climate change, and the promotion of ecosystem resilience; sociology explores the social dynamics associated with environmental movements and the societal adoption of sustainable lifestyles; and political science analyzes the governance structures and policy frameworks that address environmental challenges.

Law, in its way, shapes rules designed for environmental protection and establishes the legal responsibilities of economic and state actors. Philosophy has also seized upon sustainability, addressing the tenets of environmental ethics and of intergenerational justice, in order to encourage deeper thinking about the human-nature relationship. Anthropology offers a cultural perspective by examining the relationships different societies express in their environment. Engineering, through all its specialties, has invested in the issue of sustainability and designs technological innovations to serve a more sustainable development, while medicine and public health seek to measure and prevent the impacts of environmental degradation on human health.

This cross-cutting nature illustrates the complexity of the sustainability concept and the necessity for interdisciplinary cooperation to address contemporary environmental and social challenges. The diversity of approaches has led us to explore their extent in order to grasp the current state of sustainability as a research field and to identify emerging trends within said field through a bibliometric analysis. In order to better understand the complexity and fragmentation of sustainability research across disciplines, this article seeks to address the following research question: How has the scientific literature on sustainable development evolved over the past three decades, and what are the intellectual structures and emerging thematic frontiers that characterize this field today?

The study also aims to assess the extent to which the social and economic sciences are involved in sustainability research and to compare their contributions with those of other disciplines, such as environmental sciences, engineering, and agriculture.

A bibliometric approach is particularly well-suited to addressing this dual objective, as it enables a rigorous, systematic, and replicable mapping of scientific output, citation dynamics, and knowledge structures. Unlike traditional literature reviews, this method provides an objective assessment of contributions, collaboration networks, and emerging trends, thereby offering a comprehensive synthesis of the field's development.

Understanding the structure and evolution of sustainability research is essential for several stakeholders. For researchers in sustainability and environmental science, this analysis highlights conceptual gaps and new interdisciplinary frontiers. For policy-makers and institutional administrators, the identification of leading institutions, productive countries, and emerging research trends informs strategic investment and collaboration priorities. Finally, for the scientometric community, this study contributes methodological insights into the analysis of large-scale bibliographic data across multidimensional fields, where thematic overlaps and cross-disciplinary connections are the norm.

To investigate the research question, this article is structured into several sections. Section 2 will provide a review of sustainability theories and their applications across various disciplines. Section 3 will detail the methodologies used to collect and analyze sustainable development data from 1996 to February 2025. The bibliometric analysis will focus on examining publication and citation patterns, identifying key contributors, and exploring collaboration networks among authors, institutions, and countries. Section 4 will highlight research hotspots and emerging trends through co-citation and chronological analyses, as well as the intellectual foundations of sustainable development studies. Sections 5 and 6 will discuss current research frontiers, key milestones, and influential researchers in the field. Finally, Section 7 will summarize the main findings and suggest potential directions for future research to advance the science of sustainable development.

The Scope of Sustainability

Theories of sustainability have developed, shaped by economic, ecological, and social schools of thought. Weak sustainability, stemming from neoclassical economics in the 1970s-1980s, is based on the idea of substitutability between natural capital and human or technological capital, notably defended by Robert Solow (1974) and John Hartwick (1977). In contrast, strong sustainability, promoted by Nicholas Georgescu-Roegen (1971) in his book 'The Entropy Law and the Economic Process' and Herman Daly (1977), rejects this substitutability and argues for the conservation of key natural capital, as described in his book 'Steady-State Economics'. In the 2000s, the degrowth theory (Latouche, 2004 and Kallis, 2011) called into question, quite radically, the economic growth model. The circular economy, facing the limits of the linear economy, is also rooted in two theories, which emerged in the 1970's: regenerative economics ('Regenerative Design' by John T. Lyle, landscape architect) and performance economy ('The Potential for Substituting Manpower for Energy' by Walter Stahel and Geneviève Reday, 1981). The term 'circular economy' was also taken up by German chemist Michael Braungart and American architect William McDonough (2002) to establish a model based on the reuse and regeneration of resources. The planetary boundaries theory was formulated by Rockström et al. (2009), defining nine ecological limits not to be crossed to preserve the stability of the Earth. Resilience theory, presented by Holling (1973), focused on the capacity to adapt to crises. In the 1980s, sociologists Joseph Huber (1985) and Arthur Mol (1995) introduced ecological modernization, which relies on technological and institutional innovation to reconcile growth with the protection of the environment. Lastly, environmental justice, initiated by Robert Bullard (1990) in the United States, and the father of environmental justice, focused on inequities in exposure to environmental risk. These theories were distinct, but they crossed over and maintain their impact in reference to public policies and economic and social actors, all of which are operating in a context where ecological transition is becoming urgently necessary.

METHODOLOGY

Data Collection

As part of our research on the evolution of the literature on sustainability, we conducted a scientometric analysis to identify major scientific contributions and emerging trends in this field. This approach relies on a rigorous, structured, transparent, and reproducible process, enabling an objective evaluation of publications. Unlike traditional literature reviews, scientometrics offers several advantages, including the ability to assess the research performance of individuals, institutions, and countries, while covering a wide range of topics (Zupic and Čater, 2015).

For this analysis, we extracted data from the Web of Science (WoS) database, renowned for its reliability and multidisciplinary nature. We searched for articles related to sustainable development between 1996 and 2025 using ancillary and specific keywords reflecting the various facets of the concept. This initial selection yielded 1345 records. After excluding irrelevant documents, such as conference proceedings and review articles, and a meticulous examination of titles and abstracts, we retained 549 articles, thus constituting a representative corpus of the scientific literature on sustainability. These articles form the data object of our bibliometric analysis.

Data Analysis

Relying on a bibliometric approach based on the analysis of previous bibliographic records, we endeavor in what follows to examine various aspects of the sustainable development field, notably the evolution of publications and citations, temporal dynamics, as well as the contribution of authors, institutions, and countries. To conduct this analysis, we opted for the Citespace software, which allows us to explore bibliographic data and their references to extract relevant results. It also enables us to map knowledge by creating a synthesized network of the intellectual structure of the research field. Through this mapping, we will identify the main knowledge structures, trace the historical evolution of the field, and highlight emerging trends as well as current themes in the sustainability domain.

The Current Status of CS field

Research Trends at a Disciplinary Level

To visualize the analyzed citation patterns within the sustainability domain, we employed a dual-map overlay analysis of journals to gain a comprehensive understanding of knowledge dissemination trends. The use of this overlay technique allows us to identify disciplinary concentrations in articles, highlight emerging trends through citation relationships, and display changes in citation distribution over time (Lin et al., 2023). This technique thus enables us to observe the relationships between different fields. These changes are presented in the following table:

Table 1. Citation Trends at a Domain Level

Citing region	Cited region	Z-score
Veterinary, Animal, Science	Environmental, Toxicology, Nutrition	5.50
Veterinary, Animal, Science	Economics/Economic/Political	4.08
Economics/Economic/Political	Economics/Economic/Political	2.09

Source: Authors, WoS.

Table 1 highlights citation patterns across scientific domains. A Z-score of 5.50 reflects a strong link between veterinary and animal sciences and research in environment, toxicology, and nutrition, suggesting increasing integration of environmental and nutritional concerns in veterinary studies, likely driven by issues of food safety and sustainability. A Z-score of 4.08 also shows significant citations from veterinary sciences to economics and political science, pointing to a rising interest in the economic dimensions of animal industries, agricultural policies, and health-related markets in line with SDGs 2, 3, 12, 13, and 15.

A self-citation Z-score of 2.09 in economics and political science indicates a tendency to reference within the same field, typical of disciplines with coherent, evolving theoretical frameworks. These trends reflect a growing interdisciplinarity and a more integrated approach to addressing global challenges.

Figure 1 complements these findings by visually mapping scholarly contributions to sustainability. Journals are depicted as nodes grouped by discipline, with arcs illustrating citation flows between them. This visualisation confirms the cross-disciplinary connections identified in Table 1.

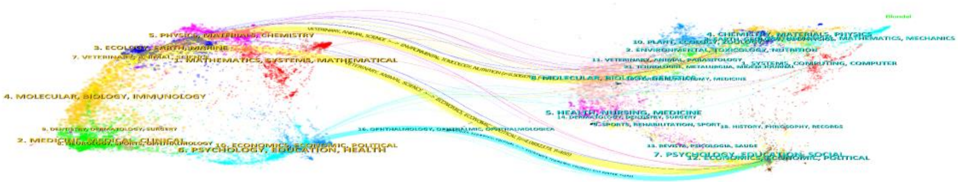

Figure 1. Dual-Map Overlay of Cited and Citing References on CS Field

Source: Authors, output CiteSpace.

Publication and Citation Pattern Analysis

The 549 selected articles have been cited 11,333 times, excluding self-citations, with an annual average of 20.77 citations per article up to the end of February 2025. The citation curve reveals that the year 2024 accumulated 2,858 citations. We also note that this analysis does not cover the entirety of disciplines and knowledge available in the field of sustainability.

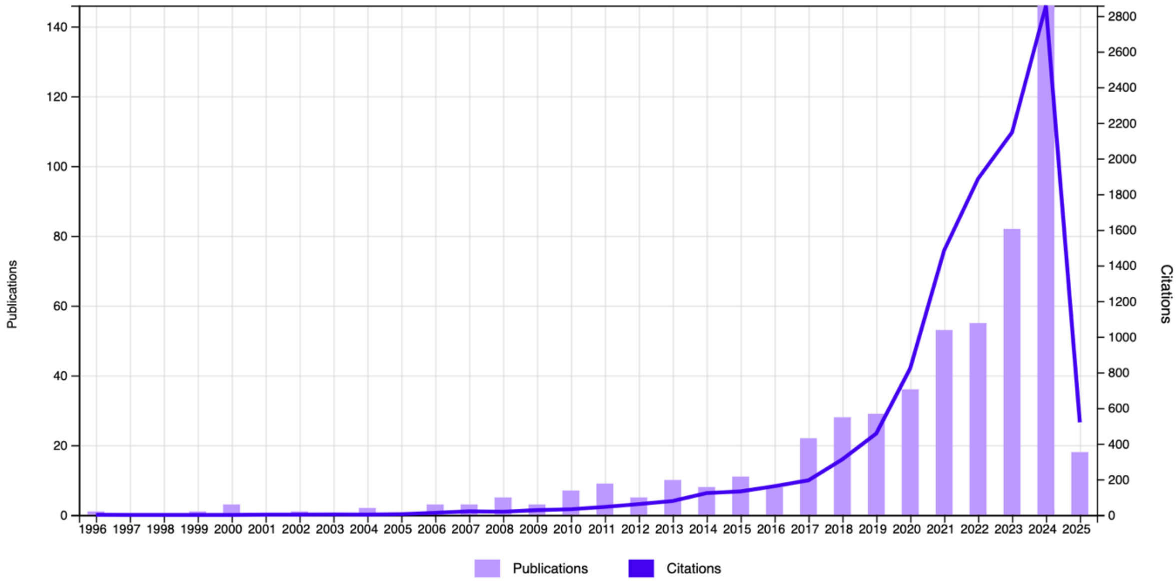

Figure 2. Times Cited and Publications over Time
Source: Authors, output WoS.

The growing volume of publications on sustainable development reflects a global awareness of environmental challenges, particularly climate change and resource depletion, which is driving governments, businesses, and researchers to rethink traditional economic models in favour of more responsible and resilient approaches. Evolving public policies and environmental regulations, shaped by international and national initiatives, are creating a favourable context for innovation and research in this area.

Major crises, such as the 2008 financial collapse and recent pandemic-related disruptions, have further accelerated interest in sustainability by exposing the fragility of growth-centric economic systems. These events have highlighted the risks of overexploiting natural resources and deepening social inequalities, prompting a shift toward models that balance economic performance with environmental stewardship, social equity, and public health.

This reorientation has intensified research and debate around sustainability, aiming to promote long-term, inclusive, and resilient development. Advances in analytical tools, modelling, and data collection are also enhancing the capacity to assess the economic impacts of sustainable policies, further fuelling academic interest in the field. Thus, we distinguish three phases in the development of publications focusing on the theme of economic sustainability:

- A sparsely represented period, namely the years between 1996 and 2009, which exhibits very low record counts (often 1 to 3 records per year), resulting in an annual publication average of only 2.44.
- A period of resurgence from 2010 to 2016, where the publication average stands at 8.29, totaling 58 publications over 6 years.
- A recent, predominant period from 2017 to 2025, during which we observe a sustained acceleration of publications, with an average of 51.63 publications per year. We note, however, a clear concentration of publications from 2021 to 2025. The year 2024 stands out with 134 records, representing nearly 24.41% of the total. The years 2023 (68 records, 12.39%) and 2022 (49 records, 8.93%) also show a high volume of publications.

Beyond the number of publications, the analysis of the top 10 most productive authors and the examination of collaborations between authors are also useful to discern the relevance of the evolution of research works on the subject of sustainability."

A Collaboration Analysis of Major Contributors to CS field

Based on the premise that scientific research relies on collaboration between researchers to produce new knowledge, we endeavor in what follows, using recorded bibliographic documents, to identify key researchers, institutions, countries, and keywords in order to map collaboration networks. These maps will allow us to visualize and explore the dynamics of scientific cooperation. In these illustrations, the size of the nodes reflects the intensity of collaboration; the larger a node, the stronger and more significant the interactions, which is manifested by thicker links. The color of the nodes reflects the evolution of the studied field, while the color density, varying between 0 and 1, indicates the degree of connectivity within the network. A value close to 1 signals strong network integration, while a value close to 0 indicates more marginal cooperation."

Co-Authorship Network

Relying on Price's Law, we have sought to identify the most productive authors. Price's Law describes the concentration of scientific publications by indicating that a minority of authors produces the majority of articles in a given field. It is useful for analyzing the distribution of scientific productivity, identifying influential researchers, and understanding the dynamics of knowledge dissemination. Based on our sample, authors who have published more than 3 articles are considered the most productive. Data analysis indicates that only 10 authors have published more than 3 articles, representing 6.37% of the total publications. This figure significantly lower than that predicted by Price's Law, which states that half of the publications on a topic are produced by a number of authors equal to the square root of the total number of publishing researchers, implying that a stable core of authors has not yet emerged in the field of sustainable development.

Table 2: Most Productive Authors in CS Domain

Authors	Record Count	% of 549
Bekun FV	5	0.911
Li X	4	0.729
Tello E	4	0.729
Wang YJ	4	0.729
Ahmad M	3	0.546
Ali S	3	0.546
Gyamfi BA	3	0.546
Haas W	3	0.546
Luukkanen J	3	0.546
Ma Y	3	0.546

Source: Authors, WoS.

The top ten authors in the co-authorship network on sustainability form a central core in the evolution of this research field. Bekun FV stands out with 5 publications, representing 0.911% of the total, while Li X, Tello E, and Wang YJ each contribute 4 publications (0.729%). The other members of this group, namely Ahmad M, Ali S, Gyamfi BA, Haas W, Luukkanen J, and Ma Y, each contribute 3 publications (0.546%). This core, although representing a modest fraction of the total 549 publications, embodies the collaborative effort and diversity of approaches mobilized to address the complex challenges of sustainability. Furthermore, the structure of this network suggests a relatively decentralized collaborative dynamic, where no single author significantly dominates scientific production. Rather than relying on a few central figures, research on sustainability seems to develop through punctual and varied contributions, reflecting a transdisciplinary and collaborative character. This diversity fosters the exchange of perspectives and innovation, while allowing environmental and economic challenges to be approached from different angles. Thus, the core of the top ten authors plays a key role in guiding research directions and stimulating interdisciplinary synergies, strengthening the scope and impact of work on sustainability.

Figure 3. Major Collaborative Authors' Groups
Source: Authors, output CiteSpace

The analysis of collaboration networks between authors is also revealing in that it allows us to understand the extent of cooperation and relationships among researchers. The network density is approximately 0.0043, meaning only 0.43% of potential connections have been realized. Such a low density highlights the weak collaboration among academic teams on sustainability themes. Nevertheless, the figure reveals two engaged collaboration groups. In the first group, we find Boldrin-Alessio, Triolo-Jin Mi, Kjaergaard-Ida, and 7 other authors from different countries and specialties. The second group, on the other hand, lists 7 authors, including Barrios-Ernesto, Wolter-Marc Ingo, and Bekun-Festus Victor. We note, however, the low collaborations in this field, both within the academic community and at the international level. While the subject of sustainability dates back decades, its resurgence is recent. Furthermore, the collaboration diagram reveals the dispersion of social science researchers and their weak academic ties. This low collaboration density among researchers is also reflected at the institutional and national levels. The analysis of collaboration networks between institutions and countries thus allows us to identify the actors most involved in sustainability research and to better understand their contribution to the advancement of knowledge in this field."

Co-Institute Co-Country Network

China leads global sustainability research with 57 publications, reflecting strong institutional engagement from key actors such as the Chinese Academy of Sciences (9), Beijing Normal University (7), Peking University (7), and others including Tsinghua University (6) and Hong Kong Polytechnic University (5). This leadership stems from China's strategic focus on ecological transition, supported by ambitious targets, carbon neutrality by 2060 and peak emissions before 2030, backed by substantial R&D investment exceeding 2.68% of GDP (2024). The country's dominance in sectors like renewable energy, electric vehicles, and international initiatives such as the Belt and Road Initiative (BRI) further consolidates its influence, despite raising concerns over global reliance on Chinese technologies.

Following China, both the United Kingdom and Azerbaijan contribute 13 publications each. The UK's output is driven by prominent institutions like the University of London (8) and University College London (5), positioning it as a leading European actor. Azerbaijan's contributions, primarily from the Ministry of Education (7) and UNEC (6), suggest an emerging national agenda around sustainability, particularly in energy.

Other notable contributors include Lebanon (8 publications), led by the Lebanese American University, and Turkey (7), with Istanbul Gelisim University at the forefront. Countries like Spain, Italy, Ukraine, Qatar, and Austria each account for 5 publications, illustrating a widening international engagement in sustainability research.
Table 3. Provides a Summary of the Most Productive Countries and their Key Research Institutions.

Table 3. Major Productive Countries

Country	Number of publications	Key Institutions (Number of Publications)
China	57	Chinese Academy of Sciences (9), Beijing Normal University (7), Peking University (7), Shenzhen University (7), Tsinghua University (6), Hong Kong Polytechnic University (5)
UK	13	University of London (8), University College London (5)
Azerbaijan	13	Ministry of Education of Azerbaijan Republic (7), Azerbaijan State University of Economics UNEC (6)
Lebanon	8	Lebanese American University (8)
Turkey	7	Istanbul Gelisim University (7)
Spain	5	Autonomous University of Barcelona (5)
Italy	5	Parthenope University Naples (5)
Ukraine	5	Ministry of Education and Science of Ukraine (5)
Qatar	5	Qatar Foundation QF (5)
Austria	5	BOKU University (5)

Source: Authors, WoS.

An analysis of the contribution of institutions in sustainable development research reveals that China is present with 6 active institutions, as noted in the following table:

Table 4: Major Productive Institutions

Affiliations	Record Count	% of 549
CHINESE ACADEMY OF SCIENCES	9	1.639
LEBANESE AMERICAN UNIVERSITY	8	1.457

UNIVERSITY OF LONDON	8	1.457
BEIJING NORMAL UNIVERSITY	7	1.275
ISTANBUL GELISIM UNIVERSITY	7	1.275
MINISTRY OF EDUCATION OF AZERBAIJAN REPUBLIC	7	1.275
PEKING UNIVERSITY	7	1.275
SHENZHEN UNIVERSITY	7	1.275
AZERBAIJAN STATE UNIVERSITY OF ECONOMICS UNEC	6	1.093
EGYPTIAN KNOWLEDGE BANK EKB	6	1.093
NORTH CHINA ELECTRIC POWER UNIVERSITY	6	1.093

Source: Authors, WoS.

Table 4, which enumerates the most productive institutions in terms of sustainability publications, expressed by the number of records and as a percentage of the total selected articles, reveals that no single institution massively dominates the field. This indicates a relatively dispersed scientific output across multiple research centers.

The Chinese Academy of Sciences leads with 9 publications (1.639% of the total), followed by the Lebanese American University and the University of London, each with 8 publications (1.457% of the total). Several other institutions, notably in China, Turkey, and Azerbaijan, exhibit similar production levels, around 6 to 7 publications.

This ranking underscore the growing importance of Asian universities, particularly Chinese ones, which occupy a major position in sustainability research. We also note a strong involvement of Middle Eastern (Lebanon, Azerbaijan, Qatar) and European (United Kingdom, Spain, Italy, Greece) institutions, reflecting a global approach to the subject. Furthermore, the exam of the institutional collaboration network, as depicted in Figure 4, reveals a low level of connectivity and emphasizes key institutions that could serve as a basis for developing stronger potential collaborations.

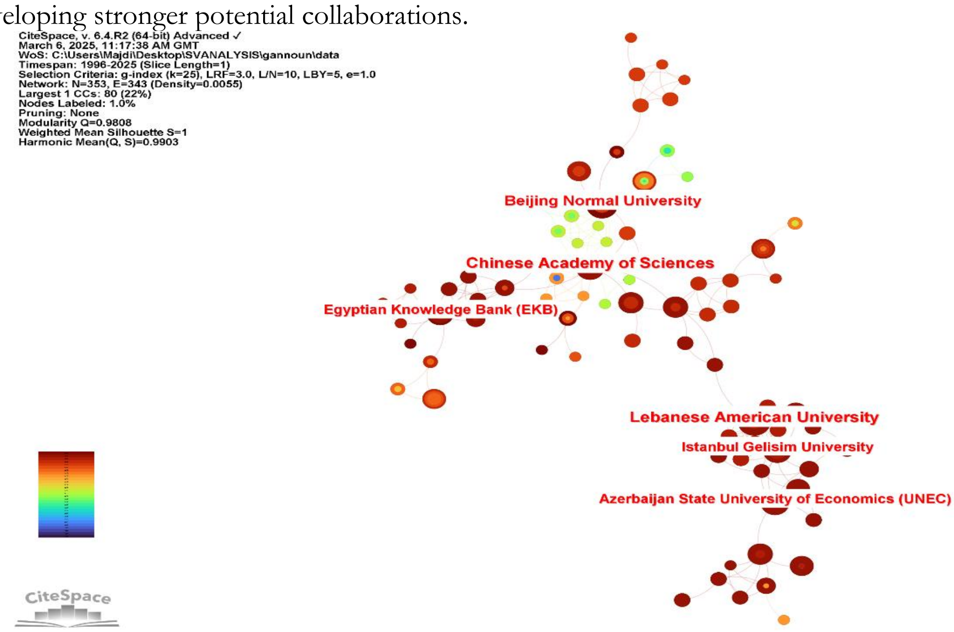

Figure 4. Most Collaborative Institutions
Source: Authors, output CiteSpace.

It is important to note that only institutions with at least 15 collaborations are included. Several significant institutions are mentioned within the network, including Beijing Normal University and the Chinese Academy of Sciences from China, the Egyptian Knowledge Bank (EKB) from Egypt, the Lebanese American University from Lebanon, Istanbul Gelisim University from Turkey, and the Azerbaijan State University of Economics (UNEC) from Azerbaijan.These institutions appear to play a central role within the network, although the overall density is low, at only 0.05%. The network indicates that collaborations among institutions are highly limited and that most institutions operate in isolation or within small groups. Furthermore, the identified institutions could serve as hubs to develop broader and more diversified collaborations. The network reveals that it is at an early stage of development, with collaborations beginning to emerge. This nascent dynamic of collaboration among institutions is also reflected in the keyword analysis, which reveals the main research themes, their evolution over time, and the actual development of research on these themes, which remain relatively recent

Keyword Co-Occurrence

Table 5 presents the top 10 keywords, each with over 40 occurrences. It underlines the central themes within the field of sustainability, which appear to primarily focus on renewable energies, the circular economy, and environmental impacts. These constitute the core of 3 clusters in Figure 5, indicating their priority in research.

Table 5. Top 10 Keyword

Frequence	Label	Year
82	Sustainability	2004
66	Emissions	2004
61	Life cycle assessment	2012
59	Energy	2012
56	CO_2 emissions	2012
55	Climate change	2009
51	Consumption	2006
49	China	2015
49	Efficiency	2012
48	Management	2000

Source: Authors, WoS.

The keyword co-occurrence map allows for the distinction of the most frequent keywords within the field of sustainability and illustrates the links of their connectivity. The network comprises 500 nodes (keywords) and 2105 edges, with a density of 0.0163, indicating moderate connectivity among the keywords. Conversely, the modularity is approximately 0.9998, signifying a network that is highly structured into distinct clusters.

These clusters are, however, not entirely isolated. Certain keywords act as bridges between the clusters, indicating transversal themes, notably including "sustainable development".

Furthermore, the evolution of these themes over the analyzed period (1988-2023) demonstrates their increasing significance over time, reflecting a growing awareness of climate and sustainability challenges.

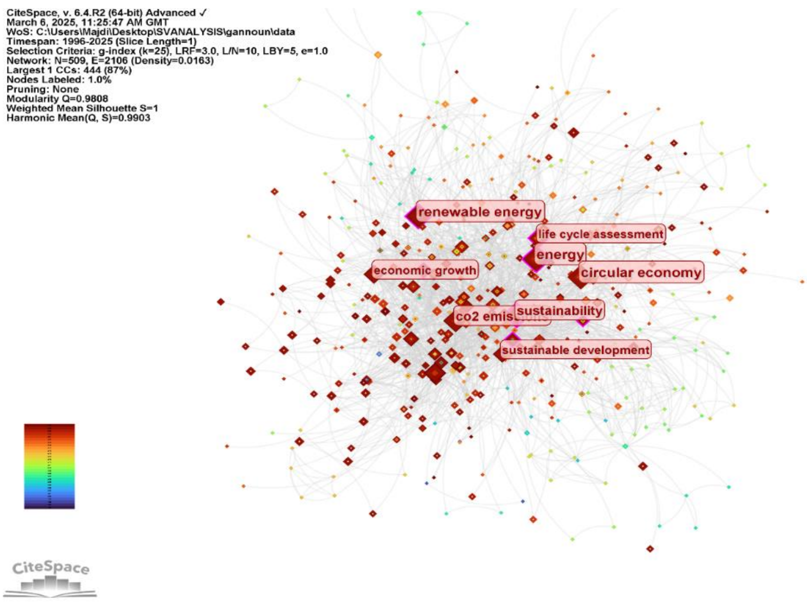

Figure 5. Keyword Co-Occurrence Map
Source: Authors, output CiteSpace.

The links between the clusters demonstrate that researchers approach the issues of renewable energies, the circular economy, and environmental impacts holistically, by integrating multiple perspectives. Conversely, less central keywords, such as 'life cycle assessment', represent emerging fields or research opportunities that are still relatively unexplored.

This distinction between central and emerging keywords also resonates in scientometric analysis, which allows for the examination of research theme evolutions and their dynamics over time, particularly through co-citation analysis.

SCIENTOMETRIC ANALYSIS: RESEARCH HOT SPOTS AND RESEARCH TREND

Co-Citation Analysis

The construction of a co-citation network relies on the representation of cited references as nodes, while their interconnections are materialized by edges (Rossetto et al., 2018). The intensity of the relationships between these nodes is determined by the frequency with which the references are cited jointly (Donthu et al., 2021). The association between cited references and reference articles is reciprocal and allows for the illustration of the evolution of ideas within a research field over time (Chen, 2006, 2020). This approach constitutes a relevant tool for mapping a scientific field and analyzing the evolution of knowledge in a given discipline. The colored arcs in the figure represent the co-citation links established during the corresponding year, thus allowing for the visualization of the dynamics of interactions within the network. The thickness of the arcs represents the weight of the co-citation and the nodes, the larger ones, indicate highly cited authors of particular interest. The network comprises five significant groups, as presented in Table 6..

Table 6. The 5 Largest Cluster

Cluster	ID	Size	Silhouette	Mean year
Resources, Growth and Sustainability	1	70	0,886	2021
Global Sustainability and Trade	2	83	0,927	2020
FinTech and Resource Management	3	69	0,986	2022
Urbanization and Natural Resources	4	79	0,976	2019
Ecosystem Valuation and Adaptation	5	29	0,966	1999

Source: Authors, WoS.

Our network analysis aims to trace the evolution of ideas within the field of sustainable development research, identifying the main thematic clusters along with their intellectual base and research front. The examination of co-citation relationships allows for a deeper understanding of the underlying dynamics of these clusters. The evaluation of the clustering approach relies on two metrics: modularity Q and silhouette. Modularity Q measures the network's ability to structure itself into distinct groups, while silhouette evaluates the internal consistency of the clusters. Thus, a high modularity score translates into a clear segmentation of the network (Chen, 2020), whereas a silhouette score close to 1 indicates an optimal separation of the clusters (Argoubi et al. 2021).

The co-citation network of sub-domains articulated around sustainability exhibits a significantly high modularity (0.9186), attesting to the robustness of its structure. The clusters are also significantly homogeneous, with a silhouette score close to unity ($S \approx 0.93$). Moreover, the five main clusters present relatively high scores. Each cluster can thus be identified and labeled according to the themes shared by its members.

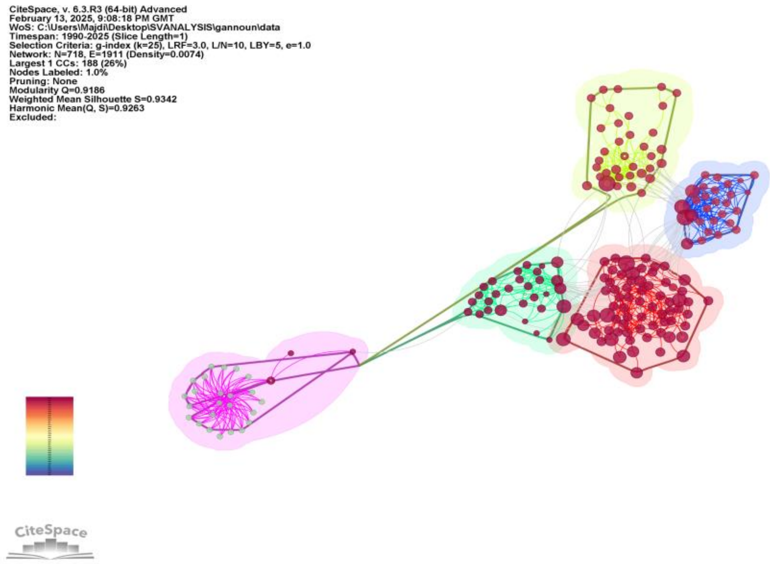

Figure 6. Co-Citation Map
Source: Authors, output CiteSpace.

Each cluster represents a coherent research theme, identified from common bibliographic references. Thus, the colors of the clusters indicate distinct thematic sets, related to different aspects of sustainability. Cluster 1 (Red): 'Resources, Growth and Sustainability' is the densest cluster, with numerous internal links. Cluster 2 (Blue): 'Global Sustainability and Trade' This cluster is more structured, with dense but internal links. Cluster 3 (Green), 'FinTech and Resource Management', reflects the growing interest in green finance, socially responsible investment (SRI), and the integration of environmental factors into economic decision-making.

This cluster is well-connected to the red cluster, indicating a link between energy transition and the development of sustainable finance. Cluster 4 (Yellow), 'Urbanization and Natural Resources', includes research on smart cities, urban pollution, and the management of sustainable infrastructures and acts as a convergence point, showing that environmental policies influence all other domains. Cluster 5 (Pink/Violet), 'Ecosystem Valuation and Adaptation', is the most isolated but remains connected to others via a few links. It highlights a critical aspect, namely environmental inequalities, climate justice, and the differentiated impacts of sustainability policies on vulnerable populations. It sheds light on social challenges, which remain underestimated in the transition towards a sustainable world, and the need to include equity considerations in environmental policies, where inequalities persist.

It is noted that the red, green, and blue clusters are dense and highly interconnected, indicating that research on energy, globalization, and sustainable finance are closely related. Furthermore, sustainability has a multidimensional character, as the overall network reveals an interaction between finance, innovation, urbanization, policy, and social justice. These clusters represent the pillars of a systemic approach to addressing sustainable development challenges.

The bibliometric map indicates several major trends in sustainability research. The co-citation network analysis reveals a strong interdependence between the different dimensions of sustainability. The 'Resources, Growth and Sustainability' cluster (Red) is central and well-connected to others, indicating that technological solutions and renewable energies are a key element of sustainability. It directly feeds discussions on globalization and its environmental impacts (Blue) and sustainable finance (Green). The 'Global Sustainability and Trade' cluster (Blue) is strongly linked to the 'Urbanization and Natural Resources' cluster (Yellow). This suggests that financial incentives and public policies play a crucial role in the transition towards a sustainable economy. The 'FinTech and Resource Management' cluster (Green) acts as a bridge between 'Resources, Growth and Sustainability' (Red) and 'Urbanization and Natural Resources' (Yellow). This indicates that urban policies must integrate technological solutions and regulatory frameworks to foster sustainable urbanization. We summarize the main characteristics of the 5 clusters in the following table:

Timeline-View Analysis

The analysis of co-citation networks in the field of sustainability over the period 1990-2025 will enable us to discern the evolution of clusters over time as well as their interconnections. We essentially distinguish two periods: an emerging one (1990-2005) where the green nodes correspond to the initial research on sustainability. However, the connections to the right indicate that certain ideas persist and influence subsequent research. And an intensification period (2015-2025) where the large red nodes show a strong concentration of recent publications.

During this period, several clusters appear, each representing a key research axis, as evidenced by the following figure:

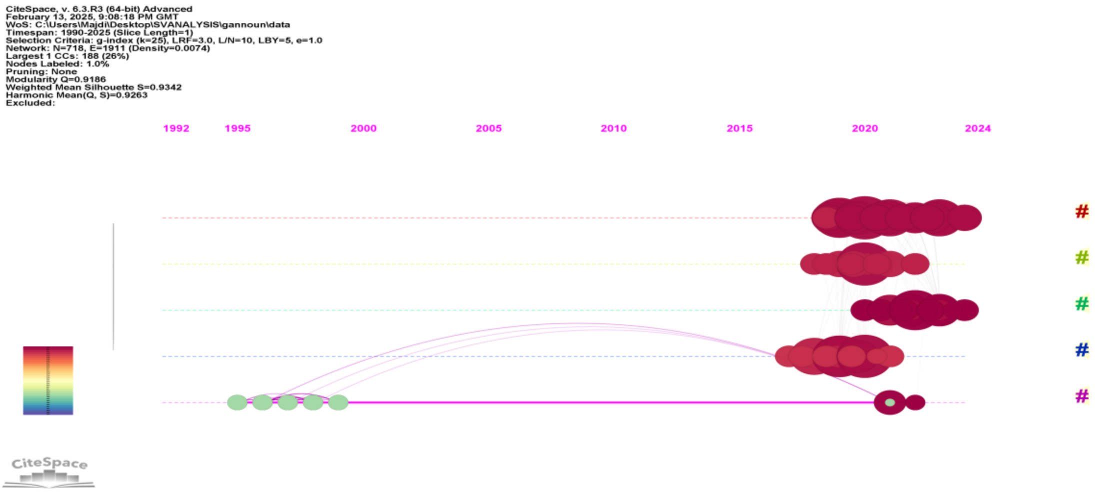

Figure 7. Network's Timeline Visualization
Source: Authors, output CiteSpace.

This figure reveals that the cluster for the 1990-2005 period is rather isolated with a strong connection to the early works on sustainability. These early works lay the groundwork for current trends. The 'Ecosystem Valuation and Adaptation' cluster seems to set the initial milestones for the central themes of the other clusters and provides a solid conceptual foundation for structuring the analysis of sustainable development. The intersection of articles from the isolated cluster with those of the other clusters thus highlights a continuity between theory and empirical application, reinforcing the robustness of the conclusions on sustainable development. The isolation of this cluster is two-dimensional due to a temporality effect, indicating that the subjects addressed at that time were precursors, but their importance has been rediscovered in the face of current climatic and ecological challenges and a poorly developed research niche, namely environmental justice.

The Intellectual Base

Cluster analysis enables the identification of underlying semantic themes as well as potential overlaps within a corpus of scientific articles (Hossain et al., 2011). Each cluster is distinguished by a specific set of characteristic terms (Waltman et al., 2010). This study focuses on the five main clusters, which, as indicated in Table 6, reflect the major research themes in sustainable development over a period of more than three decades. We will now proceed to analyze the various clusters highlighted.

Cluster 1: 'Resources, Growth and Sustainability'

This cluster includes 70 references (median year: 2021; silhouette score: 0.886), reflecting a coherent thematic focus on green growth, renewable energy, human capital, and the environmental impact of natural resource rents. It revisits the Environmental Kuznets Curve (EKC), especially in resource-dependent economies, highlighting the role of natural resource depletion in environmental degradation. However, this can be mitigated through human capital development, green innovation, and renewable energy. Trade openness appears to amplify environmental harm depending on development levels.

The cluster is grounded in the resource curse theory, emphasizing that resource rents exacerbate CO_2 emissions unless counterbalanced by sustainability policies. Key themes include the interplay between natural resources, growth, and environmental indicators like CO_2 emissions and ecological footprint.

The most co-cited paper is Zahoor et al. (2020), with 790 citations, showing how urbanization and natural resources worsen China's ecological footprint, while human capital helps mitigate this. The second most cited is Badeeb et al. (2020), which questions the EKC in resource-rich countries, revealing that resource dependence weakens the pollution-reducing effect of growth.

Recent contributions include Ayimadu (2024), using machine learning to forecast carbon emissions in Africa, and Amine (2024), examining the role of green innovation and resource rents in BRICS, underlining the tension between growth and climate targets like the SDGs and COP goals.

Cluster 2: 'Global Sustainability and Trade'

Cluter 2 includes 83 references published between 2018 and 2022, with a median year of 2020, and demonstrates strong thematic cohesion (silhouette score: 0.927). It revolves around keywords such as "carbon emissions," "economic globalization," "sustainable development goals," and "economic growth." Three main trends emerge. The first addresses the ambivalent environmental effects of globalization—either promoting green energy and sustainable finance or encouraging excessive resource exploitation. The second focuses on the role of natural resources in the energy transition: while overexploitation increases pollution (especially in G7 countries), sustainable management and innovation in Africa and the MENA region help mitigate these effects. The third highlights the contribution of finance and technological innovation to ecological transition, provided appropriate regulation is in place. The most cited article is Ali (2023), with 133 references, which examines the link between pollution, economic growth, and agriculture in sub-Saharan Africa, confirming the "polluting growth" hypothesis.

Mahmood et al. (2020), cited 504 times, argue that global integration increases environmental pressure, although technological innovation helps reduce it, supporting the Environmental Kuznets Curve hypothesis. Lei et al. (2020), with 301 citations, find that agriculture can reduce emissions in G7 countries. Lastly, two recent articles (Sampene et al. and Kaur et al., 2023) stress the dual role of globalization in emerging economies, advocating for balanced governance to align energy transition with sustainability goals.

Cluster 3: 'FinTech and Resource Management'

Cluster 3 consists of 69 articles published between 2020 and 2024, with a silhouette score of 0.986, indicating the highest homogeneity among the five clusters. The median year is 2022. All papers in this cluster explore the relationship between FinTech and environmental sustainability, emphasizing its potential to foster green finance and investment, while warning about environmental risks stemming from poor regulation. Despite differing methods, the studies converge on the idea that FinTech has asymmetric effects on climate, supporting the energy transition but requiring policy safeguards.

The leading article, "The linkages between natural resources, human capital, globalization, economic growth, financial development, and ecological footprint" by Jahanger et al. (2023), cited 457 times, underscores financial development's role in reducing ecological footprints across 73 developing countries. The second most cited, "Analyze the environmental sustainability factors of China" by Abbasi et al. (2022), with 420 citations, finds that fossil fuels drive CO_2 emissions in China, while renewable energy and long-term policies can mitigate environmental harm. A third article by Nawaz et al. (2020), with 228 citations, uses a DID approach to assess green finance's role in climate mitigation across N-11 and BRICS countries, highlighting mixed results and structural challenges.

Two recent contributions deepen the discussion. Xian (2024), in the article "Impact of Inclusive Growth, Environmental Policy Incentives, FinTech and Globalization on Environmental Sustainability in G20 Countries" (95 citations), reveals the dual role of FinTech and the importance of inclusive growth and policy incentives. Finally, Rahman et al. (2025) (91 citations) examine how renewable energy and FinTech jointly support SDG13, while fossil fuel use undermines it, using evidence from BRICS nations.

Cluster 4: 'Urbanization and Natural Resources'

This cluster, comprising 79 papers from 2017 to 2021 with a median year of 2019 and a silhouette score of 0.976, centers on three main themes: sustainable natural resource management, sustainable urbanization, and energy transition. The most cited articles include Balsalobre-Lorente et al. (2018) with 1,457 citations, Bekun et al. (2018) with 1,007, Danish et al. (2019) with 992, and Destek and Sarkodie (2018) with 759 citations.

Balsalobre-Lorente et al. (2018) analyzed the relationship between economic growth and CO_2 emissions in five EU countries, identifying an N-shaped Kuznets curve. They found renewable electricity, natural resources, and energy innovation reduce emissions, while trade openness and growth-renewable energy interactions increase them, underscoring the need for robust energy policies. Destek and Sarkodie (2018) confirmed an inverted U-shaped relationship between growth and ecological footprint in 11 newly industrialized countries, with bidirectional causality. Bekun et al. (2018) highlighted the long-term link between CO_2 emissions, resource rents, and energy consumption in 16 EU countries, showing that dependence on natural resources worsens emissions, whereas renewables improve them. Their findings stress sustainable energy policies to meet the SDGs.

Additionally, Jinru (2022), the most cited recent article with 154 references, investigates the role of environmental innovation, energy efficiency, and institutional quality in G7 nations from 1980 to 2020. The study confirms long-term positive impacts of renewable energy and innovation on sustainability, facilitated by strong institutions, emphasizing the need to strengthen policy frameworks to support clean energy transitions.

Cluster 5: 'Ecosystem Valuation and Adaptation'

The articles in this cluster converge around the integration of ecological and economic dimensions to support the sustainable management of natural resources and ecosystems. They adopt an eco-economic approach, valuing ecosystem services and emphasizing the influence of human decisions on the environment. These studies underline the importance of sustainable policy frameworks and employ quantitative models to evaluate management scenarios and promote ecosystem conservation. This final cluster includes only 29 papers published between 1995 and 2022, with a median publication year of 1999 and a silhouette score of approximately 0.966, indicating strong internal cohesion similar to the other clusters.

The most influential article in this group, with 13,483 citations, is Costanza et al.'s (1997) seminal work, The value of the world's ecosystem services and natural capital. The authors argue that ecosystem services and natural capital are essential to the functioning of the biosphere and to human well-being. They estimated their total global value to range between 16 and 54 trillion USD per year—values that, although largely outside of market mechanisms, often exceed global GDP and should be more explicitly incorporated into economic and environmental decision-making.

With 293 citations, the second most cited paper is Rasmussen et al. (1998), Long-term Agroecosystem Experiments: Assessing Agricultural Sustainability and Global Change. This study emphasizes the importance of long-term agroecosystem experiments for assessing sustainability, analyzing nutrient cycles, and forecasting environmental and climatic impacts. The authors advocate for the establishment of an international network to harmonize data collection and improve global change modeling.

Bockstael et al. (1995), with 103 citations, ranks third with their article Ecological economic modeling and valuation of ecosystems. They propose integrating ecological and economic models to improve understanding of regional systems and assess the environmental impacts of land use, development, and agricultural policies. They highlight the often-overlooked indirect, long-term consequences of policy decisions that may substantially modify conventional forecasts and assumptions.

Lastly, Evrendilek and Doygun's (2000) article, Assessing Major Ecosystem Types and the Challenge of Sustainability in Turkey, cited 66 times, provides an in-depth analysis of the environmental consequences of Turkey's rapid economic and demographic growth. The authors reveal ecosystem degradation linked to rising energy consumption and socioeconomic inequalities. They propose three sustainable policy directions: decoupling economic growth from energy consumption, promoting more equitable wealth distribution, and integrating ecological principles into economic systems by internalizing environmental externalities.

Table 7. Cluster Analysis: Most Citing Articles and Most Cited Authors

Most citing articles		**Most cited authors (in the cluster)**	
Reference	**Citation Frequency**	**Reference**	**Reference count**
Cluster 1: "Resources, Growth & Sustainability"			
Zahoor et al. (2020), "Moving towards a sustainable environment: The dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China"	790	Ayimadu (2024), "Determinants of carbon emissions in Africa: new evidence based on machine learning algorithms"	131
Ramez Abubakr Badeeb et al. (2020), "Are too many natural resources to blame for the shape of the Environmental Kuznets Curve in resource-based economies?"	125	Amine (2024), "Green technological advances and resource rents as levers for carbon reduction in BRICS: implications for sdgs 7, 8, 9, 12, and 13"	118
Cluster 2: "Global Sustainability and Trade"			
Mahmood et al. (2020), "The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: An advanced panel data estimation"	504	Ali (2023), "An empirical assessment of the tripartite nexus between environmental pollution, economic growth, and agricultural production in Sub-Saharan African countries"	133
Lei et al. (2020), "Globalization and carbon emissions: Is there any role of agriculture value-added, financial development, and natural resource rent in the aftermath of COP21?"	301	Sampene et al. (2023), "The dynamic nexus between biocapacity, renewable energy, green finance, and ecological footprint: evidence from South Asian economies"	117
Cluster 3: "FinTech and Resource Management"			
Jahanger et al. (2023), "The linkages between natural resources, human capital, globalization, economic growth, financial development, and	457	Xian (2025), "Impact of Inclusive Growth, Environmental Policy Incentives, Fintech and Globalization on Environmental	95

ecological footprint: The moderating role of technological innovations"		Sustainability in G20 Countries"	
Abbasi et al. (2022), "Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy"	420	Rahman et al. (2025), "Synergy of energy alternatives, FinTech, and natural resources on SDG13"	91
Cluster 4: "Urbanization and Natural Resources			
Balsalobre-Lorente et al. (2018), "How economic growth, renewable electricity and natural resources contribute to CO_2 emissions?"	1457	Jinru (2022), "Nexus between environmental innovation, energy efficiency, and environmental sustainability in G7: what is the role of institutional quality?"	154
Bekun et al. (2018), "Toward a sustainable environment: Nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries"	1007		
Cluster 5: "Ecosystem Valuation and Adaptation"			
Costanza et al. (1997), "The value of the world's ecosystem services and natural capital"	13483	Evrendilek et Doygun (2000), "Assessing Major Ecosystem Types and the Challenge of Sustainability in Turkey"	66
Rasmussen et al. (1998), "Long-term Agroecosystem Experiments: Assessing Agricultural Sustainability and Global Change"	293		

Source: Authors, Wos.

Research Frontiers and Major Milestones

Faced with major climate challenges, the field of sustainability has been evolving significantly in recent years, marked by the emergence of new studies and the fluctuation in the importance of certain themes. Monitoring this dynamic and analyzing the structure of co-opetition poses a challenge, particularly due to the increasing volume of publications. Rigorous scientific monitoring is essential to identify emerging trends, research advances, and the evolution of academic priorities. In this perspective, we use a temporal metric to detect surge phenomena in co-citation networks. More specifically, we apply Kleinberg's burst detection algorithm (Kleinberg, 2003) to identify citation peaks of a reference or link over a short period within the studied interval (Kumar et al., 2003). Table 8 highlights the key references that have marked their research field, with both lasting and recent impacts. It also illustrates the evolution of research priorities over several decades.

Table 8. Top 10 Burst References

Authors	Year	Strength	Begin	End	1996 - 2025
KIRCHHERR J	2020	5.13	2020	2022	
KRAUSMANN F	2006	3.88	2006	2019	
LENZEN M	2011	3.82	2011	2021	
HABERL H	2006	3.51	2006	2020	

Source: Authors, WoS.

The table presents the 5 most influential references in the field of sustainability, based on their impact strength and the duration of their citations. Kircherr et al.'s (2020) work appears to be the most influential in our sample with the highest score of 5.13, indicating a very strong influence over the period 2020-2022. The article 'Circular futures: What Will They Look Like?' highlights the transition policies towards a circular economy by proposing four plausible scenarios for a circular future. These scenarios revolve around two axes: the nature of the technologies deployed (high-tech vs. low-tech innovations) and the configuration of the governance regime (centralized vs. decentralized). The four scenarios considered, 'planned circularity', 'bottom-up sufficiency', 'circular modernism', and 'peer-to-peer circularity', show how a circular economy can be organized in very different ways, with specific advantages and disadvantages for each approach. Kircherr et al. (2020) sought to provide guidance for policymakers and businesses by offering them a clear vision of possible futures and the consequences of each scenario in order to better anticipate and shape policies and development strategies for a circular economy.

With a score of 3.88 over the period 2006-2019, the article 'The physical economy of the European Union: Cross-country comparison and determinants of material consumption', published in Ecological Economics by Krausmann et al. (2006), ranks second. This reference had a lasting impact, with 374 citations over 13 years. Through studies on the differences in material consumption between EU-15 countries, integrating ecological and sustainability issues, Krausmann et al. (2006) stressed the need for more sustainable resource management, which is essential for an effective energy transition and the reduction of the environmental footprint.

Over the period from 2011 to 2021, Lenzen's (2011) work, 'Aggregation versus Disaggregation in Input-Output Analysis of the Environment', published in Economic Systems Research, ranks third with 351 citations. With its impact score of 3.82, this reference was highly influential for 10 years. Its contribution focused on environmental analyses using input-output tables. Lenzen demonstrated that data disaggregation, even partial, is preferable to the aggregation of environmental data. According to the author, the disaggregation approach allows for a more detailed analysis of environmental impacts, which is essential for more precise and relevant eco-economic assessments.

Haberl (2006), with an older but still influential reference, ranks 4th with a score of 3.51. This reference had a lasting impact, remaining relevant for over a decade, with 163 citations over 14 years, from 2006 to 2020.

The main idea of 'The global socioeconomic energetic metabolism as a sustainability problem' is that humanity has significantly increased its energy flows over the past 10,000 years, including not only energy used in technologies but also that from food. With approximately 30% of natural resources depleted, and potentially exceeding 50% by 2050, the author raised two major sustainability problems: firstly, the depletion of energy available for natural ecosystems, and secondly, the disruption of the global carbon cycle, particularly due to deforestation and the burning of fossil fuels.

The four most influential references in the field of sustainability present varied but complementary approaches. These works provide diverse perspectives on sustainability, ranging from resource and material management to the analysis of environmental impacts and transitions towards circular economic models.

CONCLUSION

This study aimed to explore the intellectual architecture of sustainability research through an analysis of scholarly outputs between 1996 and 2025. Drawing on data from the Web of Science, the bibliometric analysis reveals a sustained growth in the volume of publications, reflecting the increasing global attention devoted to sustainability challenges. The identification of five major knowledge clusters, “Resources, Growth and Sustainability,” “Global Sustainability and Trade,” “FinTech and Resource Management,” “Urbanization and Natural Resources,” and “Ecosystem Valuation and Adaptation”, highlights the multidimensional and evolving nature of this research field.

A central contribution of this study lies in exposing the disciplinary imbalance within sustainability research. While environmental sciences and engineering dominate its intellectual core, the social and economic sciences, particularly those addressing institutional dynamics, inequalities, governance models, and production systems, remain underrepresented. Sustainability cannot be fully understood without considering the complex interactions among economy, culture, and society, which shape how resources are perceived, exchanged, and valued within diverse historical and cultural contexts.

In this perspective, we advocate for a renewed dialogue among scientific, economic, social, and cultural approaches. Future research should examine how local values, imaginaries, and economic practices contribute to redefining sustainability beyond conventional growth indicators—toward a vision grounded in social justice, cultural diversity, economic resilience, and intergenerational equity. By integrating these interdependent dimensions, sustainability research can become a genuine lever for transformative change, capable of bridging global ambitions with local realities to build more inclusive, equitable, and economically viable societies. Sustainability should not be reduced to a set of technical metrics; rather, it constitutes a shared cultural and economic horizon, where justice, memory, and human creativity emerge as the true drivers of social transformation.

Ethics and Integrity Statements

Data Availability Statement: The data used in this study were obtained from publicly available sources, primarily the World Bank database. They are available from the authors upon reasonable request.

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