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Scientific Connectivity in Space Sustainability Research: A Network-Based Study

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Space sustainability emphasizes the long-term, secure, and responsible use of outer space to ensure its continued accessibility for future generations. With the rapid expansion of space activities—driven by mega-constellations and increasing private sector participation—concerns over orbital congestion and space debris have intensified. In response, space sustainability has emerged as a global research priority. This study employs bibliometric and scientometric methods to explore the evolution of scientific research on space debris, drawing data from the Web of Science database for the period 2020 to 2024. Through collaboration and co-citation network analyses, the study identifies key research trends, influential contributors, and patterns of international collaboration. The findings provide a comprehensive view of the dynamic and interconnected research landscape supporting the global dialogue on sustainable space operations

Keywords: Bibliometrics; Scientometrics; Space Sustainability; Co-citation; Bibliographic Coupling; Cluster Analysis; Co-occurence

1 Introduction

Sustainability, as a term, has developed in parallel with international debates regarding the protection of the environment. It is best commonly characterized as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Pope, Annandale, & Morrison-Saunders, 2004)[1]. In outer space, sustainability is defined as the sustenance of long-term availability, safety, and peaceful use of space for all humanity with its socioeconomic advantages preserved for future generations.

The geometrical growth of space activities, most notably the growth of mega-constellations and heightened private sector involvement has deepened concerns regarding the sustainability of space operations. Satellites now support critical services like global communications, navigation, climate observation, and disaster response. The build-up of space debris, congestion in low Earth orbit, and lack of binding global regulations, however, pose serious challenges to the sustainable use of space.

With space becoming more an indispensable part of modern life, the need to ensure its long-term sustainability has given rise to the field of space sustainability as an important area of scientific and policy inquiry. This entails international norms, technological advancements, and policy measures to mitigate orbital debris and encourage responsible space behavior.

In order to analyze systematically the development and organization of this emerging research base, scientometric analysis is a robust method. By monitoring publication patterns, impactful authors, co-authorship networks, and thematic communities, scientometrics allows comprehensive insights into the evolution and maturity of space sustainability as a science. Such an approach is particularly beneficial due to the multidisciplinary nature of the subject, where it crosses aerospace engineering, environmental science, international law, and space policy. By doing so, researchers and policymakers are better positioned to discern knowledge gaps, future trends, and strategic imperatives to develop a more sustainable space environment.

Henry Small (1973)[2] developed the co-citation analysis as a methodological breakthrough in assessing inter-document relationships between scientific papers. By quantifying the number of times two documents are cited together, this technique indicates the latent structure and relationships among scientific fields. It has been useful for uses like Selective Dissemination of Information (SDI) profiling and mapping the intellectual terrain of research domains. This early work established the premise of using co-citation analysis to delineate emerging research fronts.

2 Review of literature

2.1 Bibliometric and scientometric approaches to space sustainability

Bibliometric analyses have become vital in mapping the intellectual structure of space sustainability research. Pulsiri and Paulino (2024)[3] examined 205 Scopus-indexed articles (2003–2022) on space sustainability, revealing dominant journals, countries, and collaboration patterns. Their VOSviewer-based visualizations provide stakeholders with tools to understand trends and interdisciplinary linkages. Paulino and Pulsiri (2022)[4] similarly conducted a bibliometric and literature review of 285 studies (2002–2021), combining quantitative mapping with qualitative synthesis. Their findings indicate a shift toward convergence in environmental and technological concerns in both Earth and space contexts.

Expanding the scope of scientometric tools, Okonta (2023)[5] analyzed 1,044 publications on sustainable procurement using VOS viewer and Gephi. Although not space-specific, this study shows how network and co-citation analysis can uncover core themes and leading actors in sustainability-oriented research. Simmons et al. (2024)[6] investigated cognitive effects of space radiation using bibliometrics. Their study provides a niche but important look at human health sustainability in space, revealing research gaps in both rodent and human subject experiments.

2.2 Theoretical and ethical frameworks for sustainable space governance

The paper by Mo, W … [et al.] (2024)[7] proposes a preliminary framework that addresses four key impact domains: (1) pollution, (2) resource depletion, (3) landscape alteration, and (4) space environmental justice. It also outlines potential metrics—including resource use, emissions data, and both midpoint and endpoint indicators—to evaluate the sustainability impacts within each domain. Several scholars propose conceptual models to frame space sustainability. Wilson and Vasile (2023)[8] coined the "space sustainability paradox," highlighting the contradiction between space's support for Earth-based (Sustainable Development Goals) SDGs and the environmental harm caused by its exploitation. Their work advocates adopting doughnut economics to balance planetary boundaries with development. Mu et al. (2024)[9] contributed a comprehensive framework for assessing space environmental sustainability, identifying four domains: pollution, resource depletion, landscape alteration, and environmental justice. The paper encourages systematic evaluation metrics for emerging technologies like in-space manufacturing. Varughesee et al. (2023)[10] emphasized integrating Indigenous knowledge and transdisciplinary perspectives in defining sustainable space futures. Studying New Zealand's New Space economy, the authors argue that diverse cultural narratives can enrich policy frameworks.

2.3 Regulatory and collaborative challenges

Legal and policy-oriented studies underscore the need for updated international governance. Bartóki-Gönczy (2024)[11] identified key regulatory gaps in space debris mitigation, space traffic management, and space resource utilization. The paper urges swift reform to prevent legal ambiguity from undermining sustainability efforts. The BSR (Business for Social Responsibility) report (2025)[12] complements this by highlighting private-sector concerns. It outlines challenges like launch emissions, orbital congestion, and lack of equitable access, recommending cross-sector collaboration and workforce diversity as solutions.

2.4 Broader sustainability research contexts using bibliometrics

Numerous bibliometric studies provide methodological and thematic analogs for space sustainability research. Raman et al. (2024)[13] reviewed 1,433 studies on SDGs and sustainability, identifying SDG 12 as dominant while highlighting the complexity of SDGs 3, 7, and 13. Baidya and Saha (2024)[14] traced climate change and sustainable development research across three decades. Thematic shifts from broad environmental issues to specific strategies like mitigation mirror trends in space sustainability discourse.

Alcaide-Ruiz et al. (2022)[15] mapped research on sustainability committees using Web of Science data, noting the cross-disciplinary nature of corporate governance and environmental accountability. Zhang et al. (2024)[16] addressed plastics and sustainability using bibliometric tools, stressing the dual challenge of production and waste. Urban and ecological health studies also offer parallels. Zhang et al. (2022)[17] linked urban green spaces with health behaviors through co-citation analysis. Mu et al. (2024)[8] extended this to blue–green space (BGS) research, revealing growing attention to nature-based solutions for climate resilience.

3. Objectives

The primary goal of this study is to analyze the current state of research productivity in the field of "Sustainability in space related activities." This is achieved through the following specific objectives:

1. To visualize co-citation network
2. To visualize Collaboration structure and Co-authorship network analysis
3. Keyword co-occurrence and cluster analysis
4. Thematic cluster analysis in research productivity
5. Identification of Research Fronts from co-citation network
6. Identify Collaborations among contributing institutions and most Influential institutions i.e. Key institutions driving the research

4. Data Collection and Methodology

Scientometric research often relies on the Web of Science (WoS)**,** a rich academic database managed by Clarivate. It brings together several major citation indexes, including the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts and Humanities Citation Index (AHCI). For this study, the data was specifically drawn from the SCIE section of the Web of Science Core Collection. The detailed search strategy used to build the dataset is shown in Figure 1.

To understand how research in space sustainability has evolved, the study uses a method called co-citation analysis. This technique looks at how often two documents are cited together in later research. When this happens frequently, it suggests that the documents share a strong conceptual link and have made a meaningful impact on the field. In other words, co-citation analysis helps spotlight the most influential studies and shows how different ideas are connected.

In the context of sustainability in space science, this method is especially useful. It allows us to map out key research themes, identify landmark publications, and see how academic conversations have shifted—from early worries about space debris

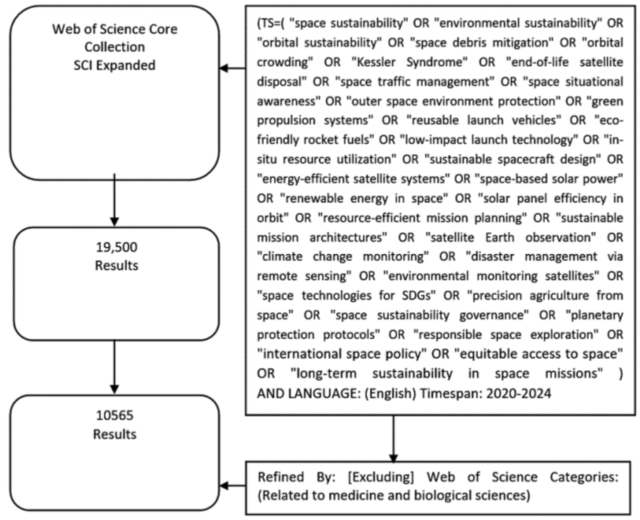

Fig. 1 — Schematic representation of formulated search strategy

to current issues like satellite mega-constellations and policy frameworks. It also highlights research gaps, points out future directions, and helps new researchers quickly find the most important work in this growing, multidisciplinary field.

5 Analysis and results

5.1. Co-citation Network Visualization

The co-citation network shown in Figure 2 offers a visual map of how research in space sustainability is intellectually structured. Two main clusters stand out.

The first cluster is built around key works by Pesaran MH (2001, 2007) and Zafar M, pointing to a strong focus on econometric models and quantitative methods. The fact that Pesaran (2007) is the most frequently co-cited paper highlights the central role these analytical techniques play in studying and forecasting sustainability-related data in space science.

The second cluster, which appears spatially distant from the first, includes influential publications like the World Commission on Environment and Development, Steffen W (2015), and Willett W (2019). This group emphasizes broad sustainability frameworks, global environmental assessments, and the Sustainable Development Goals (SDGs).

Interestingly, the weak connection between these two clusters shows that although space sustainability is inherently interdisciplinary, there's still a noticeable divide between quantitative modeling and policy-driven sustainability research. This separation in the co-citation map highlights an important opportunity which is to bridge these approaches and foster deeper

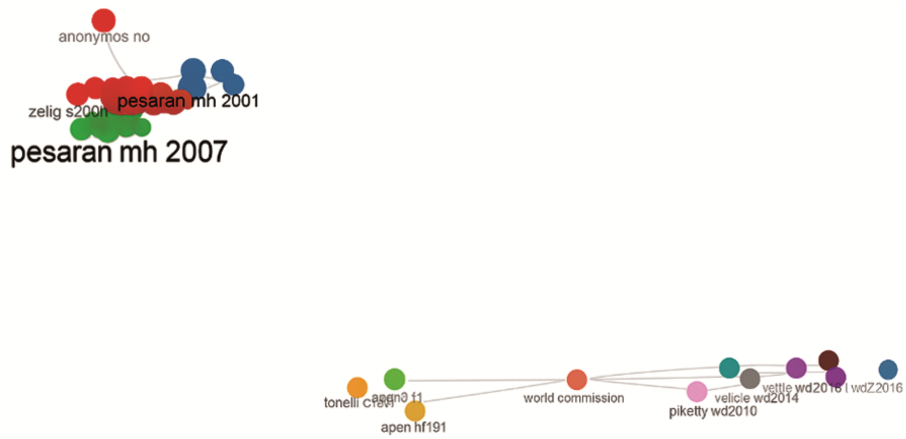

Fig. 2 — Document Co-Citation Network

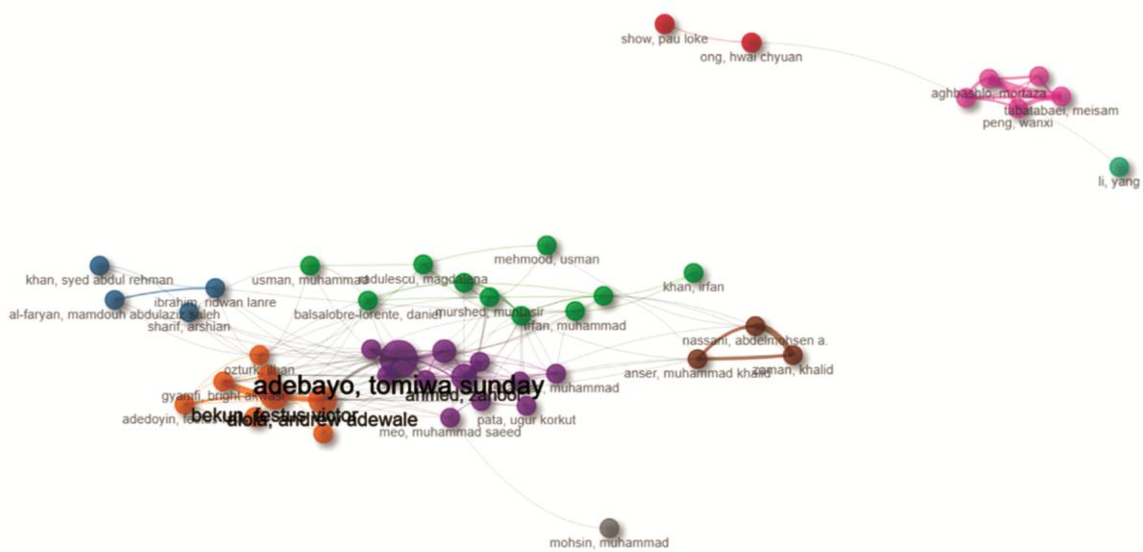

Fig. 3 — Co-authorship network visualization

cross-disciplinary collaboration, especially by linking rigorous data models with the larger goals of sustainable development.

5.2 Collaboration structure and Co-authorship network analysis

To explore how researchers collaborate in the field of space sustainability, a co-authorship network was created using bibliographic data. The resulting map (Fig. 03) visualizes the structure of author collaborations—highlighting key contributors, tight-knit research groups, and more isolated scholarly communities. In this network, each node represents an individual author, with the node size reflecting the author's publication output or influence, such as their centrality within the network. Lines (edges) between nodes indicate co-authorship ties, and colours distinguish different collaborative clusters, identified using a clustering algorithm.

At the center of the map stands Adebayo, Tomiwa Sunday, the most prominent in the network. His central position reflects a high number of co-authorships and possibly a strong role in connecting different research groups, suggesting involvement in interdisciplinary or international collaborations. Closely linked to this a few other authors are shown like Bekun, Festus and Odeyemi, Sherif Adewale etc., forming a dense sub-cluster that contributes significantly to research on energy sustainability within the space science context.

The purple cluster emerges as the largest and most interconnected group, focused on econometrics and energy-related sustainability research. Authors like

Ahmed, Zahoor are important in this cluster, adding intellectual depth to its output. Other visible groups include the green, orange, and brown clusters, along with several smaller peripheral clusters. The green cluster appears to represent a significant collaboration circle likely working on sustainable energy systems, emission modeling, or resource optimization in space technology. The orange and brown clusters are moderate in size with modest internal collaboration, possibly reflecting regional academic partnerships or thematic specializations.

Overall, the co-authorship network suggests a moderately cohesive research community, anchored by influential authors and well-defined groups. However, the presence of fragmented and peripheral clusters shows that the field is still developing, with some gaps in collaboration across regions or topics. Encouraging greater interdisciplinary and cross-regional collaboration could help bridge these gaps, integrating diverse expertise and advancing a more holistic approach to sustainability in space science.

5.3 Keyword co-occurrence and cluster analysis

The article by Callon, Courtial, and Laville (1991)[18] explores how co-word analysis can be used to study the relationships between basic and technological research, using polymer chemistry as a case study. They aim to demonstrate how this technique can map the interactions between academic and industrial research within a specific scientific field.

Here, Figure 04 is a keyword co-occurrence network map generated in Biblioshiny (or bibliometrix in R) (Aria, M & Cuccurullo, C (2017)[19]. It visualizes how frequently keywords appear together in the same documents and how those keywords form conceptual clusters in this research field. Here red cluster shown in right side is centered on Economic and environmental impact and here co2 emissions, economic-growth, impact, renewable energy etc are the key terms which indicates a focus on environmental economics, policy and emission reduction. Likewise in blue cluster the terms highlighted are performance, management, life-cycle assessment, efficiency etc. and represents engineering environmental assessment and system modelling perspectives. The grey-coloured linking lines between the two major clusters in the co-authorship network highlight important areas of interdisciplinary overlap. These connections indicate that researchers from different domains such as energy, environmental sustainability, and carbon management are beginning to work across traditional disciplinary boundaries. This overlap reflects an emerging trend in space sustainability research, where collaboration is increasingly bridging the divide between technical approaches and policy-oriented studies.

Within this interdisciplinary zone, two major conceptual themes can be identified. The first focuses on the impact of economic activities on emissions and sustainability, rooted primarily in policy, economics, and social sciences. This line of research examines how industrial activities, consumption patterns, and regulatory strategies influence environmental outcomes, especially in space-related contexts like satellite deployment or space-based energy systems.

The second theme centers on technical and performance-based environmental management, which is grounded in engineering and scientific disciplines. This includes work on emissions modeling, energy

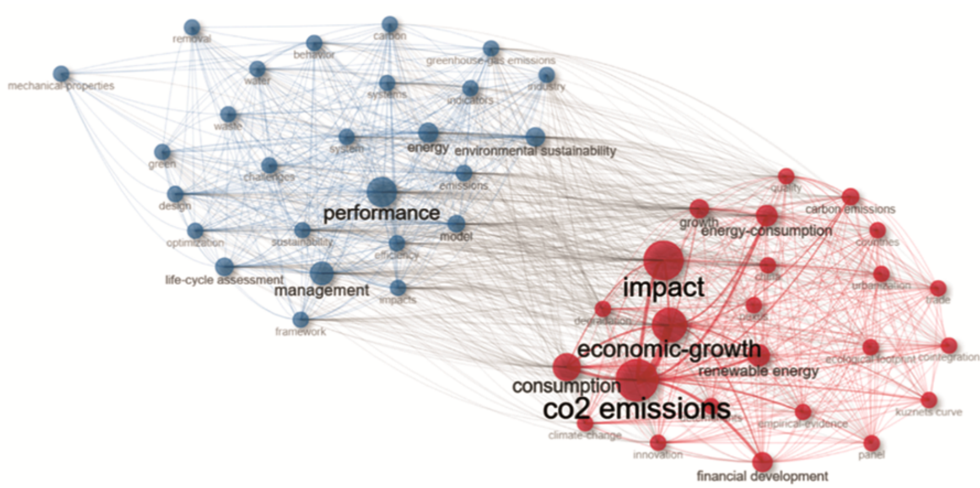

Fig. 4 — keyword co-occurrence network map

efficiency in space technologies, and life-cycle assessments of space missions or satellite infrastructure.

Together, these themes underscore the value of integrating policy insights with technical innovations. The grey links in the network are more than just lines, but they represent meaningful collaborations that can lead to more effective and comprehensive solutions for space sustainability challenges. Encouraging such interdisciplinary connections will be crucial as the field matures and seeks to address complex global sustainability goals through both scientific rigor and policy relevance.

5.4 Thematic Cluster Analysis in Research Productivity

To uncover the underlying themes in space sustainability research, a Multiple Correspondence Analysis (MCA) was conducted on author keywords using the Bibliometrix R package. This technique simplifies large keyword datasets by mapping related terms closer together in a two-dimensional space. The resulting Conceptual Structure Map (Figure 05) helps visualize how various research topics cluster based on their co-occurrence in the literature.

5.4.1 Map Overview

The map is structured along two main axes—Dimension 1 (92.51%) and Dimension 2 (2.47%)—which together capture nearly all the variation in keyword placement. Clusters of keywords reflect distinct thematic areas, with the red convex hull outlining the core conceptual space.

5.4.2 Identified Thematic Clusters

Three major thematic clusters emerged from the analysis, each representing a different intellectual direction within the field of space sustainability:

5.4.2.1 Econometric and Environmental Policy Cluster (Left Region)

This area includes terms like Kuznets curve, carbon emissions, ecological footprint, and financial development—keywords typically associated with environmental economics. These studies explore the relationship between economic activities and environmental outcomes, often using Earth-based models. Insights from this body of work can inform space policy and sustainability frameworks by drawing analogies to terrestrial systems.

5.4.2.2 Policy, Innovation, and National Development Cluster (Central Region)

Keywords such as China, growth, impact, consumption, and innovation suggest a focus on macro-level strategies, geopolitical considerations, and technological progress. This cluster reflects research that

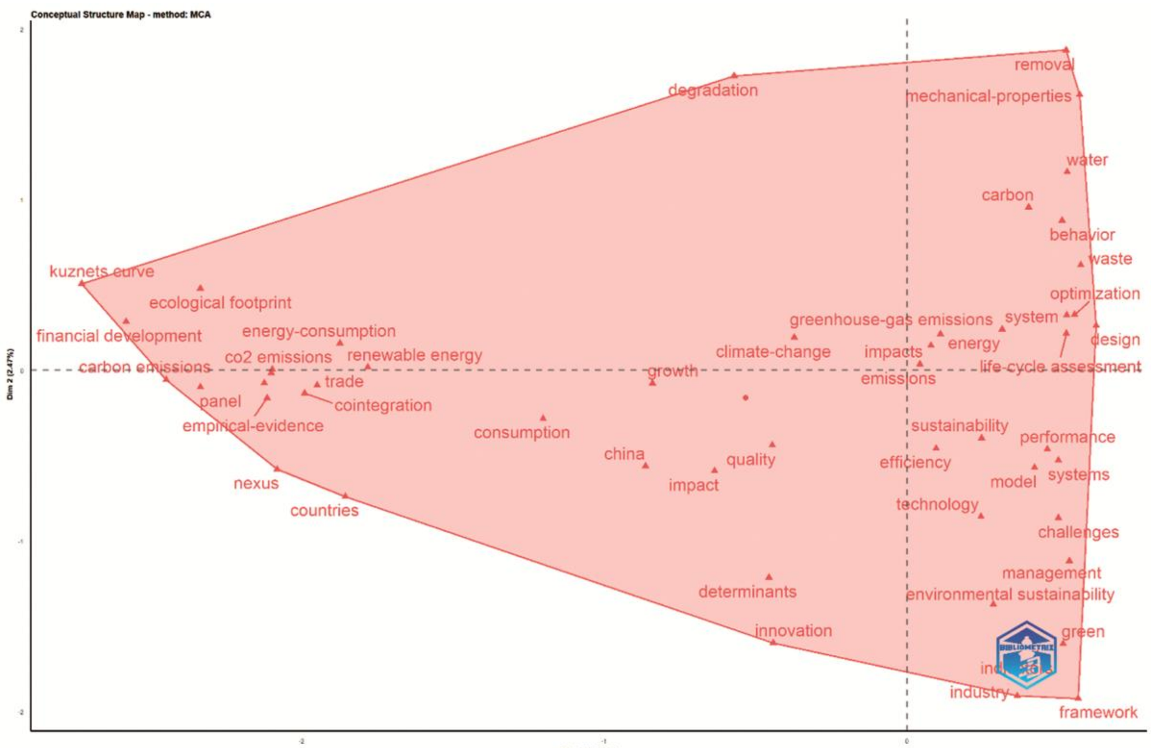

Fig. 5 — thematic structure within the corpus of space sustainability

examines how national policies, innovation systems, and strategic development contribute to sustainable practices in space exploration and infrastructure.

5.4.2.3 Technological and Systems Engineering Cluster (Right Region)

This technically focused cluster includes terms like life-cycle assessment, optimization, performance, waste, design, and efficiency. Research here concentrates on enhancing the sustainability of space systems—such as spacecraft, satellites, and habitats—through better engineering, resource management, and system-level planning. Studies often assess the environmental footprint of space technologies and propose frameworks to embed sustainability into their design and operation.

The conceptual structure map reveals that space sustainability is a deeply interdisciplinary field. It integrates perspectives from economics, policy, environmental science, and engineering, indicating that sustainable space development cannot be achieved by technology alone. Coordinated efforts across these domains are essential to build robust, future-ready solutions. This blend of macro-level policy insights and micro-level engineering innovations sets the stage for more holistic and actionable approaches in space sustainability research.

5.5 Identification of Research Fronts from co-citation network

To explore the intellectual landscape and identify emerging thematic directions in the field of space sustainability, a co-citation network analysis was performed. This analytical approach maps relationships between frequently co-cited scholarly articles, enabling the identification of research fronts and clusters of publications that represent coherent and evolving areas of inquiry within the broader field. The article by Cobo et al. (2011)[20], introduces a comprehensive methodology for tracking the evolution of a research field through detection, quantification, and visualization. Its key contribution is the development of a structured framework for mapping how a field develops over time, using visual tools to highlight major trends, thematic shifts, and interrelationships within the literature.

The resulting network visualization (Figure 06) reveals two prominent clusters, each corresponding to a distinct research front:

5.5.1 Cluster 1 (Red): Environmental Economics and Policy-Oriented Sustainability

This dominant cluster represents a well-established intellectual base in the field of environmental economics, with a strong emphasis on policy-driven approaches to sustainability. It includes influential works that focus on key themes such as carbon emissions, financial development, ecological footprint, and environmental policy. The high frequency of co-citation among these studies indicates a tightly connected scholarly community, largely grounded in macroeconomic modeling frameworks, particularly the Environmental Kuznets Curve (EKC). These models are extensively used to analyze sustainability dynamics, especially in developing economies, where economic growth and environmental protection often need to be balanced.

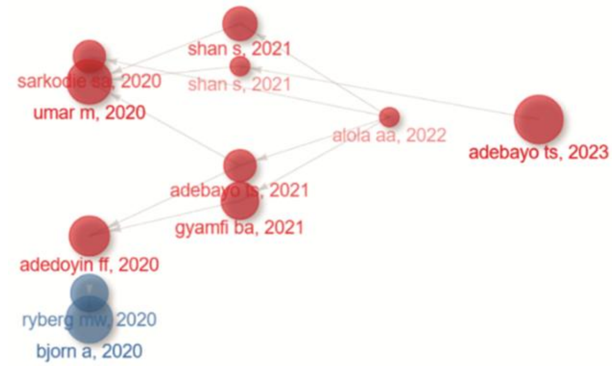

Fig. 6 — Author Co-citation network

A particularly noteworthy node within this cluster is the work by Adebayo TS (2023), which stands out due to its central and recent positioning in the co-citation network. Its prominence suggests the emergence of a new research front, potentially expanding the application of terrestrial environmental models to guide space governance and sustainability policies. This represents a significant step toward conceptualizing space sustainability within broader economic and regulatory paradigms.

5.5.2 Cluster 2 (Blue): Technical and Life-Cycle-Based Sustainability Approaches

The blue cluster, though smaller in size is distinct and methodologically focused on technical and engineering-driven sustainability solutions. Key contributors in this group include Ryberg MW and Bjorn A, whose work emphasizes life-cycle assessment (LCA), system performance evaluation, and optimization techniques. Research in this cluster typically addresses the environmental efficiency and sustainability performance of technologies used in space missions, satellite systems, and other space infrastructure.

The relative separation of this cluster from the red (policy-focused) cluster reflects a clear methodological divide. However, this divide also highlights opportunities for interdisciplinary integration, particularly in the design and management of sustainable space systems. A crucial bridging node between these two domains is the publication by Adedoyin FF (2020). Its co-citation with both policy-oriented and technical studies suggests a hybrid approach, merging economic-environmental modeling with engineering perspectives. This points to a promising avenue for cross-domain collaboration, where holistic strategies can be developed by combining strengths from both fields.

Overall, the co-citation analysis reveals a research landscape that is both structurally mature and intellectually dynamic. The field is characterized by:

- A solid foundation in terrestrial environmental policy and macroeconomic modeling,
- A growing body of work centered on technical innovations and engineering-based sustainability solutions, and
- Increasing efforts to synthesize insights across disciplines.

These emerging research areas show how the field of space sustainability is growing and changing. They suggest that in the future, combining smart policies with advanced technologies will be key to making space activities more sustainable

5.6 Collaborations and Influential Institutions and Key institutions driving the research

The analysis of country-level collaboration in the field of space sustainability was conducted and visualized through both network graphs and geographical maps. The primary goal was to gain insight into how different nations contribute both individually and collectively to the global research agenda, aimed at ensuring the long-term sustainability of outer space activities.

This analysis reveals a diverse and evolving landscape of international collaboration. Using data on Single Country Publications (SCP) and Multiple Country Publications (MCP), the study examines the extent to which countries are engaging in domestic versus cross-border research partnerships. These metrics, depicted in Figure 06 and Figure 07, help differentiate between self-contained national research efforts and collaborative international projects. Through network diagrams and spatial visualizations, patterns of cooperation are clearly mapped.

Figures 07 and 08 provides a comprehensive visualization of global contributions to space sustainability research. In these figures, node colours represent distinct regions or key contributing countries, while the thickness of connecting lines (edges) indicates the strength of collaboration measured by the number of co-authored publications. Larger and more central nodes, such as those representing the United

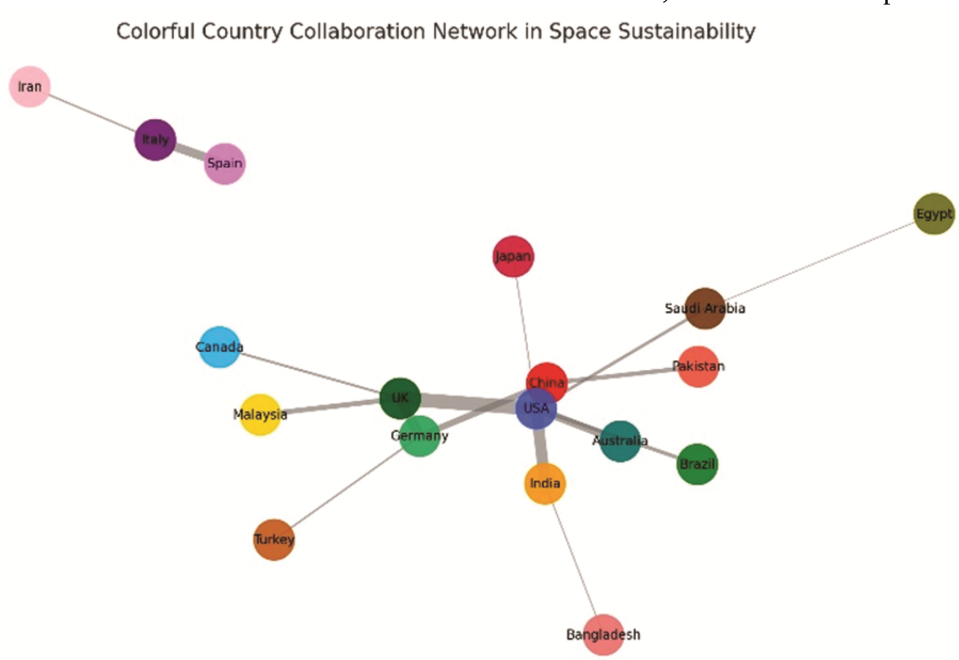

Fig. 7 — Geographical visualisation of collaborating countries

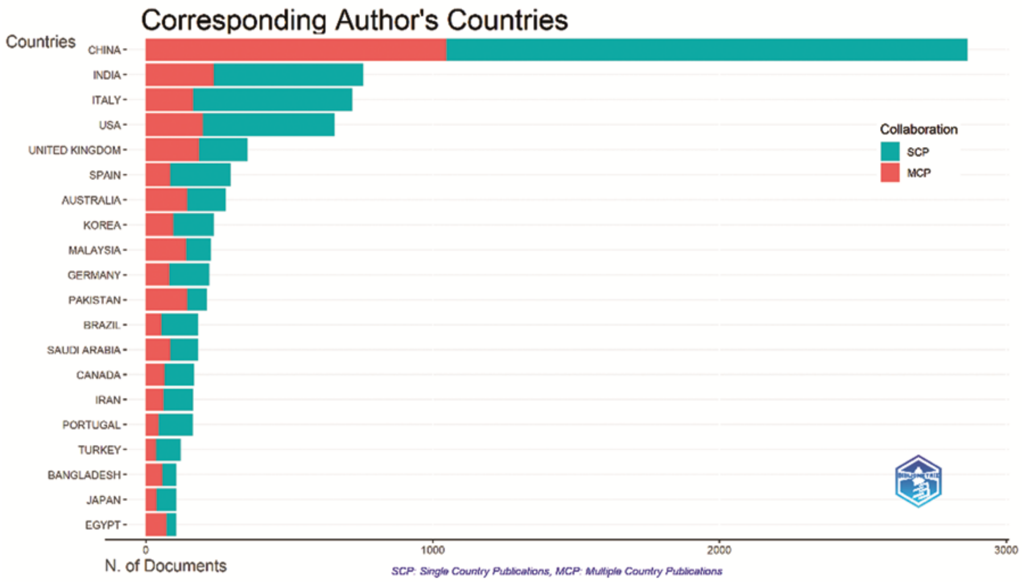

Fig. 8 — Country-wise distribution of articles

States, the United Kingdom, and China, signify countries with extensive collaborative ties and high publication output. These nations act as central hubs in the global research network.

In contrast, smaller nodes such as Bangladesh, Egypt, and Iran appear more regionally connected, participating in fewer or more localized collaborations. Their involvement, while modest, signals emerging contributions from regions that may be underrepresented but are gradually increasing their presence in the global dialogue on space sustainability.

Overall, this analysis highlights the importance of international collaboration in advancing knowledge and shaping policies for space sustainability. It also underscores the need for inclusive global partnerships, ensuring that contributions from a wide array of countries regardless of size or resources are integrated into the collective effort to protect the space environment for future generations.

5.6.1 Collaborations and Influential Institutions

Figure 07 presents a geographical visualization of international collaborations in space sustainability research. It highlights the centrality of countries like the United States, the United Kingdom, China, and India within the global research network. The United States stands out as the most interconnected node, forming extensive bilateral ties across continents, especially with China, India, the UK, and Australia. This dominant position underscores its influence not only in research output but also in driving global partnerships and collaborative agendas. The UK also shows a high degree of global connectivity, particularly with Europe and Commonwealth nations, as reflected in its high Multiple Country Publication (MCP) ratio. Its strategic engagement in multilateral initiatives such as EU-funded research programs and policy platforms further reinforces its role as a global research bridge.

On the other hand, countries like China and India, although heavily represented in the network, show a preference for domestic collaborations, indicated by their relatively high Single Country Publication (SCP) values and lower MCP ratios. While they maintain selective international partnerships especially with the U.S. and other spacefaring nations their collaboration profiles remain closely aligned with national research priorities. European countries such as Germany, Italy, and Spain display active regional collaborations, often facilitated by frameworks like the European Space Agency (ESA) and the European Union, promoting coordinated scientific efforts across borders. Meanwhile, emerging contributors including Pakistan, Bangladesh, Saudi Arabia, and Egypt are increasingly engaging in international collaborations, often relying on strategic alliances to gain access to technology and expertise. However, vast regions, especially in Africa and Central Asia, remain significantly underrepresented in the collaboration network, revealing structural gaps in research capacity and access.

Figure 08, which shows the country-wise distribution of publications, complements the collaboration patterns by highlighting the dominance of a few major contributors. The United States leads in total research output, followed by China, the United Kingdom, and India. While these countries are central to global knowledge production, their modes of collaboration differ considerably. The U.S. and the UK show strong engagement in multinational research, while China and India continue to prioritize internal research ecosystems. Other nations, despite lower output, contribute through focused or regional collaborations, often shaped by policy, funding availability, or strategic interest in space sustainability.

Together, Figures 07 and 08 reveal a hub-and-spoke model of collaboration, with a few influential countries acting as central hubs, connecting with a broad set of partners across the globe. This structure emphasizes the need for a more inclusive and equitable research environment. Increasing participation from underrepresented regions—particularly in the Global South—requires targeted capacity-building, supportive funding models, and accessible international collaboration platforms. Encouraging multinational missions and interdisciplinary, transnational research consortia will be key to ensuring a more balanced and globally coordinated approach to addressing the complex challenges of space sustainability.

Overall, the findings suggest that international collaboration in space sustainability research follows a hub-and-spoke model, wherein a few central countries such as the United States, the United Kingdom, and China— as primary hubs of knowledge production. These nations facilitate and lead much of the global research effort, while a broader set of countries contributes through targeted, often bilateral, partnerships. To foster a more equitable and robust global research ecosystem, it is essential to enhance participation from the Global South, where many nations currently remain under-represented. This calls for inclusive research frameworks, capacity-building initiatives, and greater investment in cross-border collaboration platforms. Additionally, expanding multinational missions and encouraging interdisciplinary, transnational research consortia can help bridge existing gaps and drive more comprehensive and globally coordinated solutions to space sustainability challenges

5.6.2 Key institutions driving the research

Figure 09 identifies the most prolific research institutions contributing to scholarly output in the field of space sustainability. Leading the chart is the Chinese Academy of Sciences (CAS), with 413 articles, establishing it as the foremost global institution in this area. This reflects China's strategic emphasis on space science and sustainability, driven by robust state funding, infrastructure, and a clear national agenda for leadership in outer space activities.

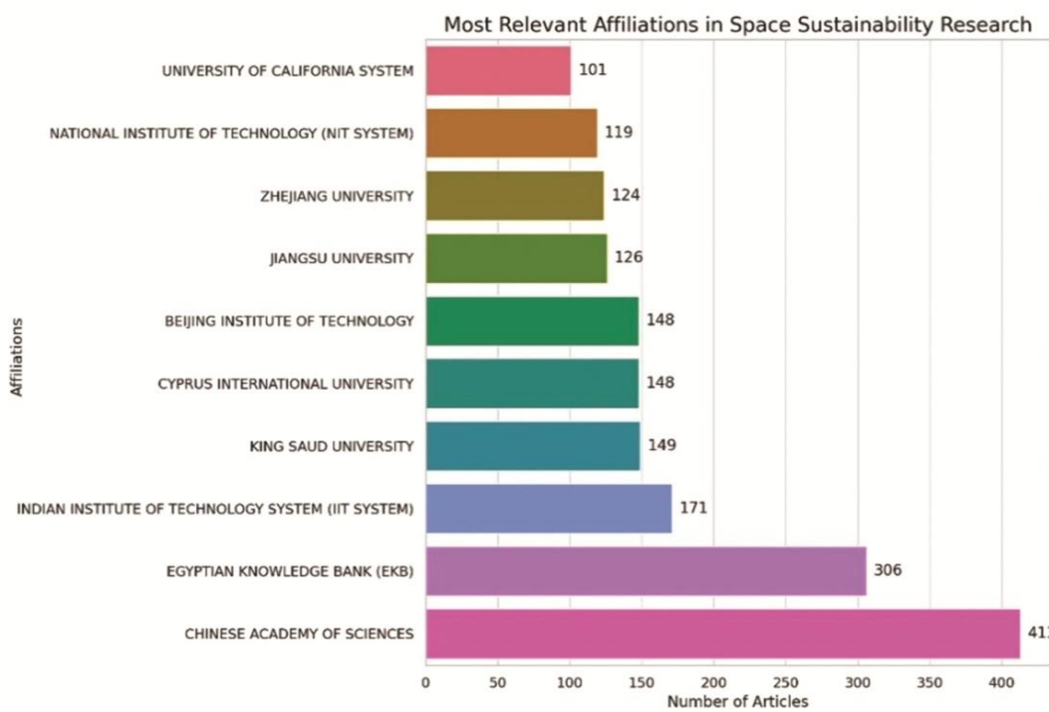

Fig. 9 — Most relevant institutions contributing to space sustainability research

The Indian Institute of Technology (IIT) System, spread across various campuses in India, ranks third with 171 publications. This underscores India's strong academic engagement through its premier technical institutions, reflecting its increasing commitment to sustainable space development. Other significant contributors include King Saud University (149 articles) and the Beijing Institute of Technology (148 articles), demonstrating the rise of Middle Eastern and additional Chinese institutions in the global space sustainability discourse.

Notably, institutions such as Cyprus International University, Jiangsu University, and Zhejiang University, each with over 120 publications, signal the expanding contributions of regional and emerging academic centers. These universities often engage in interdisciplinary research and international collaborations, further enriching the global research ecosystem. The University of California System, the only U.S. based institution in the top contributors list (with 101 articles), illustrates American academic involvement, though its output appears modest when compared to the dominance of Chinese institutions.

This shift in institutional leadership indicates that while traditional space powers like the United States continue to participate, China and India now lead in publication volume, driven by national science, technology, and innovation policies. The inclusion of the Egyptian Knowledge Bank (EKB) among top contributors also points to a new trend where national-level digital repositories or research consortia play a pivotal role in aggregating and disseminating research. Furthermore, the active participation of universities from countries like Saudi Arabia and Cyprus highlights how emerging nations are embedding space sustainability into their scientific agendas. These efforts are often integrated into broader strategies for international engagement and national development through science and technology. Overall, institutional contributions to space sustainability research have evolved beyond the domain of elite space-faring nations. The field now exhibits a multi-institutional and multinational character, where both leading research academies and regional universities contribute significantly to the global dialogue.

As shown in Figure 10, the cluster analysis of institutional collaboration reveals that research in

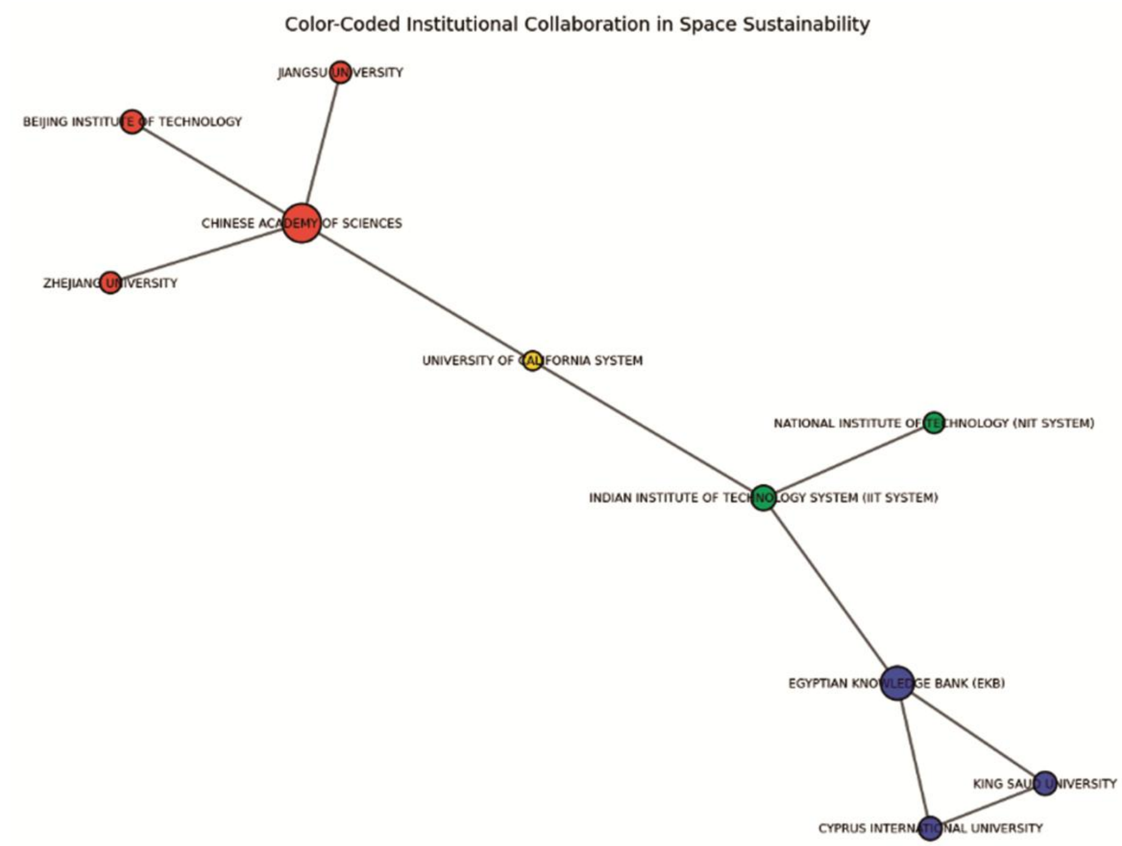

Fig. 10 — Institutional collaborations in Space sustainability

space sustainability is shaped by a combination of strong regional alliances and strategic international linkages. Institutions in China, India, and Egypt emerge as key players, with CAS and EKB acting as central nodes in the network. These institutions not only produce a high volume of research but also serve as anchors for broader collaborative frameworks.

The analysis highlights that cross-regional collaboration, particularly between institutions in Asia (e.g., China and India) and North America, plays a vital role in facilitating knowledge exchange and fostering technological integration. These ties are essential for developing globally aligned approaches to sustainable practices in space. In conclusion, the current institutional landscape suggests fertile ground for deeper inter-institutional partnerships, especially among high-output institutions. Enhanced collaboration can support the development of inclusive, globally coordinated strategies for space governance, environmental stewardship, and the long-term sustainability of orbital activities.

5.7 Evolving Research Trends

The clustered network graph provided in Figure 11 picturizes and provides the hint like evolution of Sustainability Research from theory to application, rising role of data and optimization and interdisciplinary convergence. Sustainability research has undergone a notable transformation, evolving from its early foundations in economic theory and policy analysis to a present-day emphasis on practical, performance-based strategies. This shift reflects a growing urgency for implementable solutions to pressing environmental and climate-related challenges, moving beyond theoretical discourse toward measurable impact.

A key feature of this evolution is the increasing reliance on quantitative tools, modeling techniques,

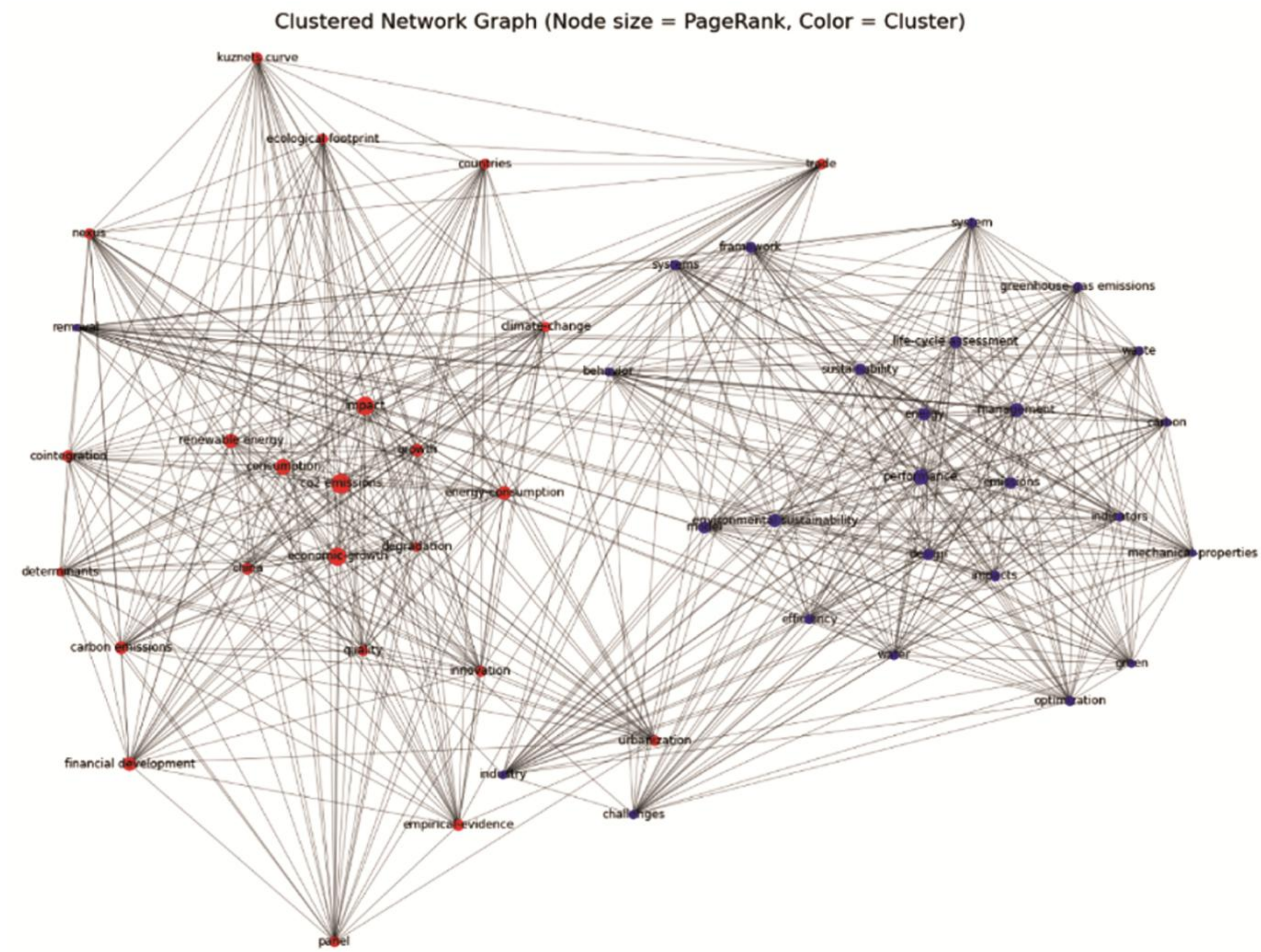

Fig. 11 — Clustered network graph

and structured decision-making frameworks. These methodologies enhance both the rigor and transparency of sustainability efforts, offering policymakers and practitioners data-driven insights to guide effective interventions. Modern sustainability literature is also marked by its interdisciplinary character, integrating knowledge from fields such as engineering, economics, public policy, and behavioral sciences. This synthesis fosters a more holistic and systems-oriented approach to addressing global sustainability concerns, recognizing the interconnectedness of technological, social, and ecological systems. Looking forward, future research is expected to increasingly explore emerging domains such as the circular economy, green innovation, artificial intelligence (AI) applications in sustainability, and climate resilience strategies. These areas promise to shape the next frontier of sustainability science, offering innovative pathways for mitigating environmental degradation while promoting socio-economic development. Recognizing these thematic and temporal shifts is essential for scholars and practitioners. It enables alignment with emerging research priorities, supports the design of cross-disciplinary studies, and enhances contributions to both policy formulation and technological advancement in sustainability.

6. Findings

As space exploration gains momentum, the need to ensure it unfolds responsibly is more urgent than ever. Major findings are the following:

First, the co-citation network provided a window into the intellectual backbone of the field. It identified the key thinkers and foundational studies that shape how we understand sustainability in space—ranging from managing the environmental impact of space missions to modeling complex systems. The structure of the network also reflects a healthy blend of environmental science, aerospace engineering, and public policy—demonstrating the field’s inherently interdisciplinary nature.

Second, the co-authorship and collaboration maps revealed a moderately connected global research community. While strong collaborations exist, especially among institutions in North America, Europe, and parts of Asia, the overall network still shows signs of fragmentation. This suggests an expanding cross-regional and cross-disciplinary partnerships could accelerate innovation and help address the global nature of sustainability challenges in space.

Third, by examining keyword patterns and thematic clusters, two major research directions came into focus. One is driven by big-picture economic and policy concerns i.e. topics like carbon emissions, financial development, and renewable energy. The other is more technical, exploring performance optimization, life-cycle assessment, and engineering solutions. This dual focus shows that the field is not just growing, but it’s maturing, and increasingly aiming to deliver actionable results.

Fourth, the timeline of research topics shows a noticeable shift. Earlier studies were largely theoretical and policy-driven. But recent work is much more grounded in engineering and system-level approaches, emphasizing how sustainability can be built into the design of space missions, materials, and operations. It's a sign that the conversation is moving from "why" to "how."

Finally, the study highlighted several exciting frontiers in the field. Topics like sustainable satellite design, space debris management, in-situ resource utilization (ISRU), and green propulsion technologies are gaining traction. These aren’t just niche interests, but they represent a growing recognition that sustainability must be at the heart of how we plan and conduct future space missions.

7. Conclusion

The study provides a comprehensive overview of the recent trends and thematic developments in the field of sustainability in space science, focusing on literature published between 2020 and 2024. Guided by five key objectives, the analysis integrated multiple scientometric techniques to uncover structural patterns and emerging research fronts. In conclusion, this study demonstrates that sustainability in space science is evolving into a distinct and rapidly growing research domain, characterized by increasing inter-disciplinarity and practical orientation. The insights generated from this analysis can serve as a strategic guide for researchers, funding agencies, and policy stakeholders seeking to align their efforts with the most impactful and innovative directions in sustainable space development.

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