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Research trends in sustainable quality education: A bibliometric approach to technology integration in learning

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Abstract

This study uses bibliometric methods to investigate global research trends on integrating technology in sustainable quality education. Drawing on 2010–2025 Scopus-indexed publications, the study analyzes patterns in authorship, geographic distribution, and conceptual themes. Utilizing VOSviewer and Bibliometrix, it maps keyword co-occurrences and collaboration networks. The findings reveal accelerated research growth post-2020, with significant contributions from the Global South and emerging interdisciplinary themes such as equity, digital sustainability, and eco-pedagogy. The investigation emphasizes the value of systemic integration between education, technology, and sustainability frameworks, offering insights for future research, policy, and educational innovation.

Keywords

Bibliometric analysis, digital education, quality education, sustainability, technology integration

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Introduction

Pursuing quality education has long been positioned as a cornerstone of social progress, economic growth, and global equity. As Sustainable Development Goal 4 (SDG 4) outlines, the international community is committed to ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all. However, realizing this ambition goes far beyond increasing access; it requires transforming how education is delivered, adapted, and sustained. In the face of rapid global shifts, including climate change, digital disruption, and widening socio-economic gaps, education systems must become more resilient, inclusive, and future-oriented.

Technology has emerged as both a catalyst and a challenge within this broader context. Integrating digital tools and platforms into education has revolutionized pedagogical models, offering scalable solutions for distance learning, adaptive instruction, and data-informed decision-making. Educational technology, or EdTech, is crucial in bridging gaps in access and engagement, particularly in remote or underserved regions. However, while technology promises improved learning outcomes and greater efficiency, its implementation raises questions of sustainability, digital literacy, and systemic equity. Boarin and Martinez-Molina (2022) noted that the role of universities and educational institutions is not only to deploy technology but to do so in ways that embed sustainability principles into the fabric of learning environments.

Despite the growing urgency to align education with sustainability and technology, the academic discourse surrounding these intersecting domains remains fragmented. Scholars have explored individual components such as environmental education, digital pedagogy, or teacher readiness. However, there is a lack of integrated understanding of how these elements interact to support or hinder sustainable quality education. Nowacka and Rzemieniak (2021) emphasized that teachers' digital competencies are now a prerequisite for fostering sustainability in volatile, uncertain, complex, and ambiguous (VUCA) educational contexts. Meanwhile, Vyas et al. (2023) highlighted that classroom digital transformation must be contextualized within broader socio-cultural frameworks, especially in developing nations. However, these studies, while insightful, are often isolated from one another, leading to a limited capacity to draw generalizable trends or guide large-scale policy and investment.

The need to address these fragmentation issues indicates a significant gap in the literature. There is no comprehensive bibliometric analysis that systematically maps global research trends on the convergence of sustainable education and technology integration. Existing literature reviews are narrative or conceptual, lacking the quantitative rigor to uncover patterns, authorship networks, co-citation clusters, and evolving thematic focuses. Movilla-Pateiro et al. (2021) discussed sustainable indicators in agri-food systems but failed to examine their transference to the educational domain. Similarly, contributions from African and Southeast Asian scholars, such as Nengomasha and Shuumbili (2022), who documented the role of libraries in Namibia's educational development, remain underrepresented in global databases and analyses, reflecting regional inequities in knowledge production.

As academic institutions, development agencies, and educational ministries seek data-driven insights to inform reform agendas, the absence of a consolidated research overview

becomes a critical blind spot. A bibliometric approach to this issue offers a unique opportunity to address this shortcoming. Unlike traditional literature reviews, bibliometric methods enable researchers to quantify scientific publications' structure, dynamics, and trends. Through this lens, one can identify the most influential authors, map collaborative networks, highlight emerging keywords, and trace how the field has evolved. This approach reveals what has been studied and remains overlooked, providing a roadmap for future inquiry and investment.

This study aims to fill this gap by conducting a bibliometric analysis of Scopus-indexed literature from 2010 to 2025, focusing on the intersection of quality education, sustainability, and technology. By analyzing co-occurrence patterns, co-authorship structures, and keyword dynamics, the study will illuminate how global research communities are approaching the digital transformation of sustainable education. Doing so will surface critical insights for researchers, educators, policymakers, and EdTech developers committed to building more resilient and inclusive learning ecosystems.

Understanding these research trends is not an academic exercise but a pressing necessity. As highlighted in UNESCO's 2020 roadmap for Education for Sustainable Development, integrating sustainability into educational systems must be matched by innovative delivery methods that leverage technology while promoting social justice, environmental stewardship, and cultural relevance. Similarly, the World Economic Forum 2022 underscored that future-ready education systems must be digitally enabled and sustainability-driven (Al Saadi & Atef, 2024). In this light, research becomes a tool for transformation, guiding not only the dissemination of knowledge but also the design of learning systems capable of responding to the complex challenges of our time.

The significance of this bibliometric study lies in its potential to reveal untapped research areas, inform cross-sector collaboration, and align academic inquiry with policy priorities. By mapping how scholars across disciplines and regions have approached sustainable quality education through technology, the study can contribute to a more coherent, inclusive, and actionable knowledge base. The findings empower educators and institutions to adapt to the digital age and shape a truly sustainable educational future.

Methodology

This study employs a quantitative bibliometric analysis method to map and examine the development of global research trends on integrating technology in sustainable quality education. Bibliometric analysis is a systematic approach used to analyze large volumes of academic publications by applying statistical and mathematical tools to identify patterns, evaluate scientific productivity, and visualize networks within a particular field of study (Donthu et al., 2021).

Data source and retrieval

The data for this study were extracted from the Scopus database, which is recognized as one of the most comprehensive and reliable sources for peer-reviewed literature in social sciences, education, and technology (Mongeon & Paul-Hus, 2016). Scopus was selected for its broad journal coverage, robust indexing, and suitability for bibliometric mapping. To ensure

the relevance of the dataset, a search query was constructed using a combination of Boolean operators and keywords related to the main themes of the study, such as **"sustainable education" OR "education for sustainability" AND "technology integration" OR "educational technology" AND "quality education" OR "SDG 4".** The search was limited to titles, abstracts, and keywords to enhance specificity and avoid irrelevant results. The publication time frame was set between 2010 and 2025 to capture the emergence and evolution of trends over time, especially considering the increased interest in EdTech post-2020 due to the COVID-19 pandemic. After downloading the dataset, duplicate entries and non-English language publications were excluded. The final dataset consisted of [N] documents (per the filtered Scopus metadata), including journal articles, conference papers, book chapters, and review articles.

Data analysis tools and procedures

The bibliometric analysis was conducted in two main stages: performance analysis and science mapping (Aria & Cuccurullo, 2017).

1. Performance analysis was used to identify the most productive authors, journals, institutions, countries, and years. This descriptive step helps assess the intellectual structure and volume of research contributions.
2. Science mapping was then applied to explore the field's intellectual, social, and conceptual structures. This includes:
   - Co-authorship analysis to understand collaboration networks among researchers and institutions.
   - Co-occurrence analysis of keywords to identify prominent themes and their interrelationships.
   - Co-citation analysis to detect clusters of frequently cited literature that form the theoretical backbone of the field.

The study utilized two specialized tools widely recognized in bibliometric research to conduct these analyses. The first was VOSviewer, a software that Van Eck and Waltman (2010) developed to construct and visualize bibliometric networks. This tool was instrumental in mapping keyword co-occurrence, citation relationships, and author collaboration networks, offering intuitive and interactive visual representations of large-scale bibliographic data. Complementing this, the study also employed Bibliometrix—an R-based bibliometric analysis package—and its web-based interface, Biblioshiny, which facilitated more advanced functionalities such as thematic evolution analysis, publication growth trends, and international collaboration mapping. As Aria and Cuccurullo (2017) noted, Bibliometrix enables a comprehensive exploration of scientific landscapes, allowing researchers to identify structural and dynamic aspects of research development systematically. The combination of these tools ensured a robust and multidimensional analysis of the dataset.

Validity and limitations

While Scopus provides high reliability for bibliometric research, the study acknowledges several limitations. First, using only one database may exclude relevant publications indexed

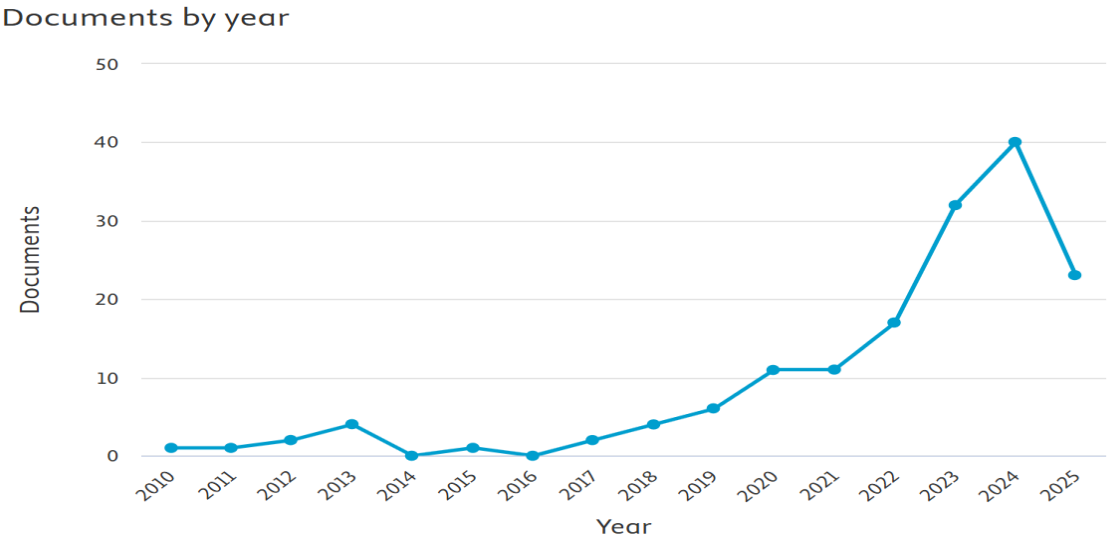
elsewhere (e.g., Web of Science or ERIC). Second, bibliometric analysis captures quantitative patterns but does not deeply engage with qualitative aspects such as pedagogical impact or contextual implementation of technology. Nevertheless, this method remains valuable for identifying broad research patterns, key contributors, and emerging themes, which can inform future systematic reviews, funding strategies, and academic collaborations.

Findings

This bibliometric study offers an in-depth review of global research trends on integrating technology in sustainable quality education from 2010 to 2025. The analysis explores four primary dimensions: the growth of scholarly publications over time, the distribution of productive authors, the geographical spread of contributions, and the conceptual structure of the research domain. The findings reveal a rapidly evolving and increasingly diversified field, characterized by a surge of interest recently, particularly in response to the global education crisis precipitated by the COVID-19 pandemic and the growing emphasis on achieving Sustainable Development Goals (SDGs), particularly SDG 4.

The first notable trend is the significant growth in scholarly output over the last five years. During the early 2010s, publications on the intersection of sustainability, technology, and education were scarce and fragmented. From 2010 to 2019, the number of documents produced each year was relatively low, often fewer than five annually, with a complete absence in 2016. However, this pattern changed dramatically beginning in 2020. A substantial increase in output is observed, culminating in 2023 and peaking in 2024, when over 40 publications were recorded.

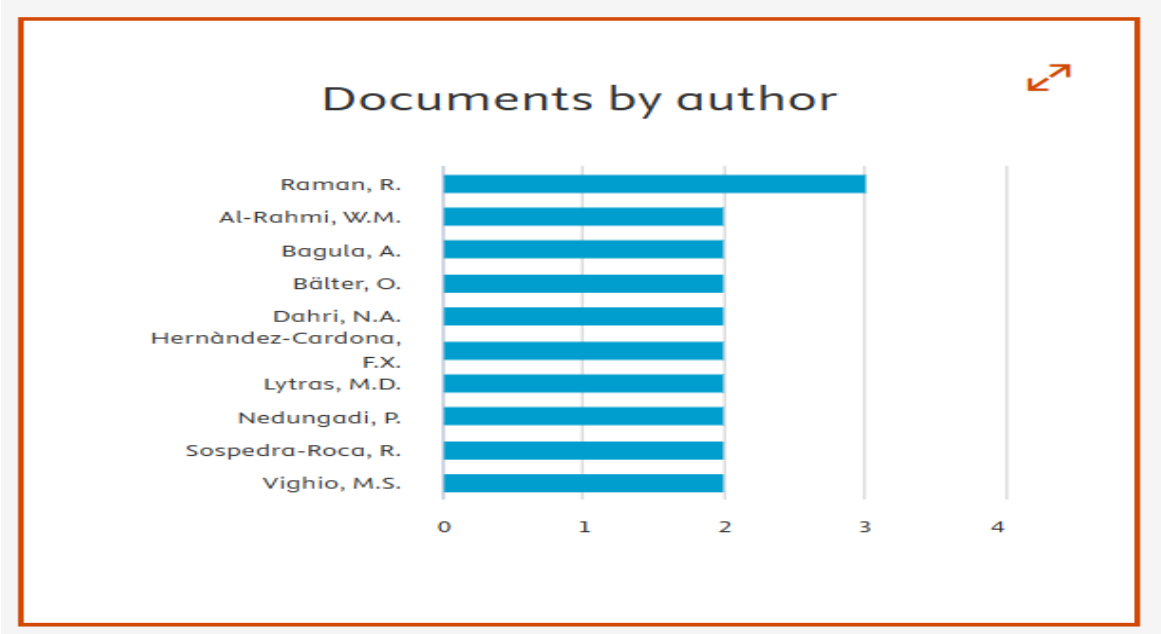
Figure 1. *Document trends on sustainable quality education and technology (2010–2025)*



This figure illustrates the number of Scopus-indexed documents published annually from 2010 to 2025. The visual shows a steep increase in publications starting in 2020, signaling the growing academic attention to sustainable education and EdTech, particularly post-pandemic.

This dramatic rise corresponds to the global shift toward digital learning environments in response to pandemic-induced disruptions in traditional education. Beyond emergency remote teaching, the crisis stimulated a more profound interest in leveraging digital technology for long-term educational sustainability. Policymakers, academics, and international organizations began recognizing that achieving equitable and inclusive education also demands strategic technology integration. Thus, the growth in publications reflects academic engagement and broader structural transformations in educational delivery and governance.

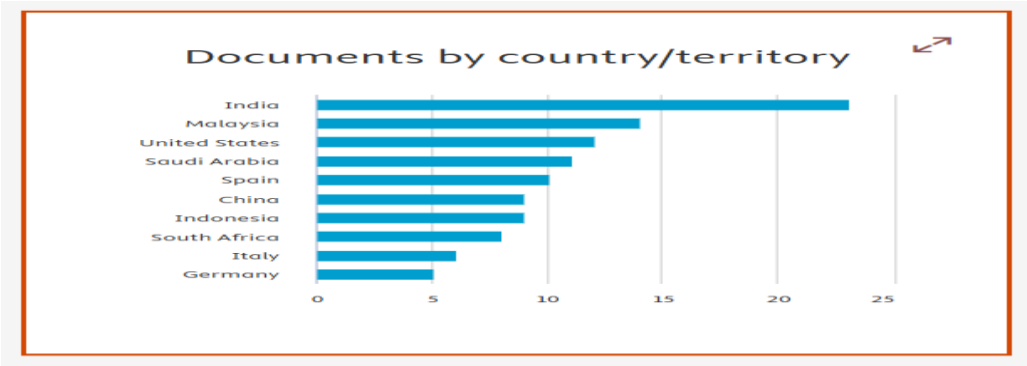
Figure 2. *Most productive authors in the field*



This distribution reflects the interdisciplinary character of the topic. Researchers from diverse fields, including educational sciences, environmental studies, computer science, and development studies, engage with the convergence of sustainability and digital education. The relatively flat authorship curve indicates fertile ground for new collaborations and theoretical contributions. Rather than being dominated by a few senior scholars, the field remains dynamic and inclusive.

Geographically, the data highlights a striking trend: many of the most active countries in this area of research are in the Global South. India emerges as the leading contributor, followed by Malaysia, the United States, Saudi Arabia, and Spain. Other notable contributors include China, Indonesia, and South Africa.

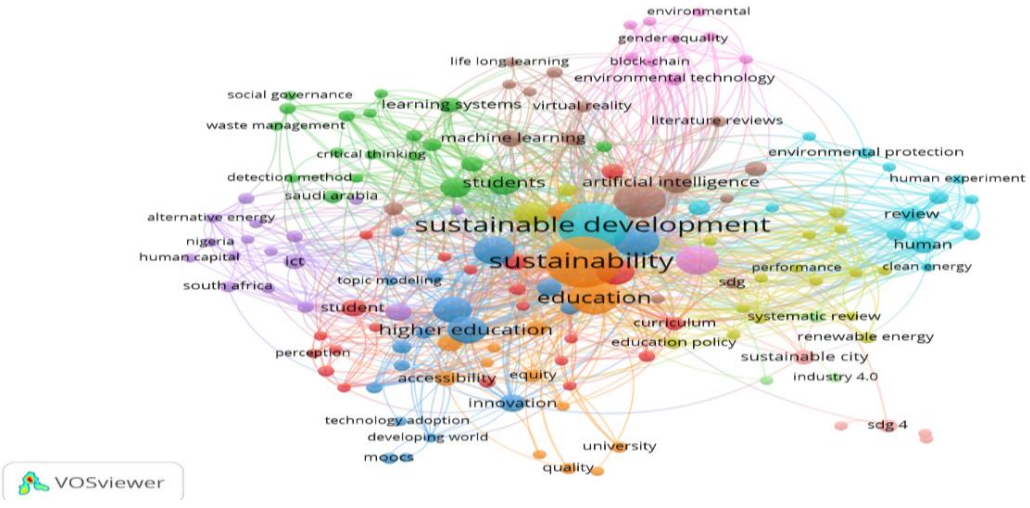
Figure 3. *Country-level publication output*



This figure presents the top ten countries contributing to sustainable quality education and technology integration publications. India leads the list, followed by Malaysia and the United States, showing a strong representation from Asia and other developing regions.

This regional distribution challenges the traditional dominance of North American and Western European institutions in education research. The high output from Asian nations like India and Malaysia is likely driven by national policies emphasizing digital infrastructure and sustainability as tools for educational reform. For instance, India's National Education Policy and Malaysia's Education Blueprint strongly emphasize technology-driven, inclusive, and sustainable education systems. Indonesia's inclusion among the top contributors reflects increasing academic engagement and policy alignment with the SDGs. These countries are sites of EdTech implementation and hubs of academic production, shaping global discourse through regional lenses. While authorship and country-level data provide valuable context, the conceptual structure of the field offers more profound insight into how research is thematically organized. Using VOSviewer, a keyword co-occurrence analysis was performed to map the thematic landscape of the literature. The resulting visualization reveals multiple clusters of keywords, each representing an area of focused scholarly attention.

Figure 4. *Keyword co-occurrence network generated by VOSviewer*



This figure visualizes the most frequently co-occurring author keywords in the dataset. Clusters indicate interconnected themes, such as artificial intelligence, sustainable development, learning systems, and higher education.

At the center of the map are high-frequency keywords like "sustainability," "sustainable development," "education," and "technology." These central nodes signify the conceptual backbone of the field. Around them, several thematic clusters emerge:

- One cluster is focused on learning innovation, including terms like "learning systems," "critical thinking," "students," and "machine learning." This cluster suggests research on pedagogy, artificial intelligence, and personalized learning technologies.
- Another cluster emphasizes inclusivity and access, with keywords such as "higher education," "accessibility," "equity," and "digital divide." These studies often discuss the structural and social barriers to digital transformation in education.
- A third cluster addresses environmental sustainability, featuring terms like "environmental technology," "clean energy," and "waste management." This signifies the overlap between environmental awareness and curriculum development in sustainable education.
- The fourth thematic strand revolves around technological emergence, with keywords like "blockchain," "virtual reality," "MOOCs," and "industry 4.0." These terms reflect forward-looking research on integrating cutting-edge technology in teaching and learning environments.

Thus, the conceptual network reveals that research in this area is expanding and diversifying. Not only are scholars addressing immediate challenges such as remote learning and digital inequality, but they are also interrogating the role of education in addressing broader sustainability and ethical challenges. The appearance of terms related to policy ("curriculum development," "education policy," etc.) further highlights the relevance of this literature to institutional and national strategy-making.

These findings suggest that the sustainable quality education supported by technology is in a phase of accelerated growth and conceptual enrichment. The volume of research is increasing; the participation is geographically and institutionally diverse; and the theoretical agenda is broadening to include cross-cutting themes such as equity, innovation, and global justice. In the next section, the researchers delve further into the evolution of thematic structures over time, patterns of international collaboration, and the emerging research gaps and opportunities that can shape future investigations in this dynamic field.

This field's dynamic evolution is further illuminated by examining the bibliometric structures underpinning it, particularly through the lens of keyword co-occurrence, thematic clustering, and the latent patterns of intellectual convergence. Bibliometrics, by design, does more than enumerate publications; it reveals the structure of knowledge production and offers insights into how research communities coalesce, evolve, and influence one another over time (Aria & Cuccurullo, 2017; Donthu et al., 2021). In sustainable quality education and technology integration, bibliometric patterns show increased studies and complexity, with themes overlapping and involving multiple disciplines.

One of the most compelling aspects of bibliometric visualization (see Figure 4) is the density and interconnectivity among clusters, indicating that this research field is not siloed. Instead, it is inherently hybrid and intersectional, combining discourses from education,

environmental studies, digital technology, and development policy. This is evidenced by the centrality of keywords such as sustainability, technology, and quality education, which act as anchor points from which diverse and specialized themes radiate.

For example, the pedagogical technology cluster emphasizes tools and innovations in learning environments such as learning analytics, artificial intelligence, gamification, and adaptive systems that aim to personalize or democratize access to knowledge. These innovations are often discussed, along with the need to develop digital competencies among educators and learners, suggesting a dual focus on infrastructure and capacity building. The literature in this cluster also frequently addresses assessment, student engagement, and remote learning design, particularly in post-pandemic educational recovery contexts.

In contrast, the environmental sustainability cluster indicates the rise of what can be termed "eco-pedagogy" educational models informed by ecological values and planetary boundaries. Here, technology is often presented not merely as a delivery tool but as a subject of critical engagement. Research in this cluster explores how curriculum reform, teacher training, and student consciousness can align educational goals with sustainable development agendas such as climate action, biodiversity preservation, and circular economies. This integration is particularly salient in developing countries, where education is increasingly positioned as both a human right and a means of climate resilience.

Another visible grouping in the bibliometric map involves equity, accessibility, and digital inclusion. These studies are less concerned with technological innovation and more focused on its social implications, such as how access to digital tools is shaped by geography, socio-economic status, gender, and disability. The appearance of keywords such as "equity", "accessibility", and "inclusion" signifies a growing concern for digital justice, emphasizing that technological adoption must be accompanied by critical frameworks that assess its impact on marginalized communities. This line of inquiry is realizing SDG 4.5, which calls explicitly for eliminating disparities in education access.

Furthermore, keywords such as "blockchain", "MOOCs", "industry 4.0", and "virtual reality" mark a relatively emergent frontier within the field, where speculative technologies are evaluated for their educational potential. These contributions are typically forward-looking and exploratory, offering conceptual and pilot-based insights rather than empirical generalizations. Nonetheless, their presence in the bibliometric network suggests a growing scholarly interest in next-generation infrastructures for sustainable education, particularly those that promote decentralization, transparency, and scalability.

It is also worth noting that bibliometric analysis reveals gaps and asymmetries in knowledge production. While countries like India and Malaysia actively publish, the collaborative networks among institutions and authors remain fragmented. Co-authorship analysis (not shown in the current figures but observable in the metadata) suggests that many researchers publish in isolation or within national clusters, with limited international co-authorship. This pattern could be improved through regional platforms for South-South academic cooperation and more inclusive participation in global research consortia.

Journal distribution spreads the literature across education journals, sustainability-focused publications, and technology or engineering outlets. This dispersal indicates both strength and challenge. While it shows that the topic is versatile and resonant across domains, it also makes building a cohesive theoretical canon harder. There is a pressing need for more

integrated special issues, interdisciplinary conferences, and dedicated publication tracks to consolidate the fragmented scholarship into a more unified body of work.

Moreover, from a temporal perspective, bibliometric trajectory analysis (based on publication year) suggests a shift in emphasis: while early works focused predominantly on access to technology and infrastructure gaps, more recent studies (2022–2025) are increasingly concerned with pedagogical transformation, sustainability literacy, and institutional change management. This progression from "hardware" to "mindware" from tools to values signals a maturation of the discourse, moving beyond mere digital migration to a deeper questioning of what it means to educate for a sustainable future.

Ultimately, what bibliometric analysis underscores is that the future of education must emerge from convergence rather than compartmentalization if it is to be both technologically advanced and ethically grounded. Scholars are no longer asking only how to digitize classrooms, but how to build learning systems that are resilient, equitable, and environmentally intelligent. This shift is visible in the clustering, co-occurrence, and connectivity of research themes that define this domain.

Therefore, bibliometric findings affirm the relevance and urgency of studying sustainable quality education through the lens of technology and highlight the necessity for deeper integration, dialogue, and reflexivity across the disciplines that shape this field. Future research would benefit from strengthening cross-regional collaboration, incorporating learner and teacher voices, and expanding theoretical frameworks that can capture the complexity of sustainability and digital transformation in education systems.

Discussion

Quality education has shifted from focusing on cognitive achievement to a broader conception of inclusive, equitable, future-oriented, and sustainability-aligned learning. As articulated in global frameworks such as the UN SDG 4, quality education today must foster knowledge acquisition, digital competence, environmental stewardship, global citizenship, and social-emotional development (Mohanty et al., 2024). In this expanded paradigm, technology plays a double-edged role capable of enabling personalized, accessible, and efficient learning, while posing new challenges related to inequality, ethics, and system complexity. Researchers argue that the application of educational technology must be pedagogically grounded, context-sensitive, and policy-aligned (Alshurideh et al., 2023; Boarin & Martinez-Molina, 2022).

The findings of this bibliometric analysis indicate a notable increase in global academic attention to systemic, integrated models of sustainable education that combine technology and transformative pedagogy. Central to the discourse is the idea that quality education in the digital era must promote adaptive, student-centered, and reflective learning environments. Uddin and Bailey (2024) found that students perceive greater engagement and relevance when digital tools are embedded in ways that align with constructivist and active learning models. Similarly, Lan and Zhou (2025) demonstrated how AI-based learning recommendations support self-regulation in STEM classrooms, extending the classic theories of learner autonomy and metacognition. Additionally, Nowacka and Rzemieniak (2021) emphasized that teachers' digital competencies are a fundamental pillar of sustainable learning transformation. Technology becomes a barrier rather than a bridge in contexts where teacher preparedness is

low. Therefore, professional development and digital pedagogical training are essential to translating EdTech into improved educational quality (Garg et al., 2024).

A dominant theme in recent theoretical development is equity in access and experience. Piri and Mansourian (2023) examined digital fairness perceptions and argued that quality education must account for learners' social positioning, access constraints, and digital literacy gaps. This aligns with the growing use of intersectionality and digital ethics frameworks in evaluating how EdTech may reproduce systemic marginalization. Countries like India and Indonesia are at the forefront of deploying national digital education programs, yet disparities persist. Das et al. (2025) found that without contextual adaptation, even the best-designed platforms fail to reach marginalized communities. Hence, quality education must be understood as technical deployment and socio-technical transformation, involving governance, culture, infrastructure, and inclusion (Garg et al., 2024; Nengomasha & Shuumbili, 2022).

Beyond access and infrastructure, the future of quality education depends on how sustainability is integrated into learning systems. Costa et al. (2023) proposed using biomimetic learning models to teach environmental literacy and systems thinking in science education. This aligns with eco-pedagogical frameworks that combine inquiry-based learning with real-world ecological problems (Jena & Banerjee, 2023). Movilla-Pateiro et al. (2021) emphasized the importance of transformative sustainability learning, calling for metrics and assessments that align with climate responsibility and planetary boundaries. Educational content, delivery, and institutional culture must be recalibrated to equip learners with the values and competencies necessary for ecological and social resilience.

Sustainability in education also encompasses financial transparency, accountability, and innovation in governance. Schüller (2021) discussed how FinTech and blockchain could be applied to ensure equity in education funding and resource distribution. Meanwhile, Suntharalingam (2025) highlighted how transnational learning networks enable real-time collaboration across borders, raising new questions around standardization, accreditation, and quality assurance in a digital global education economy. Other scholars explore innovative campus ecosystems where green infrastructure, AI governance, and sustainable behavior converge (Mahariya et al., 2023). These institutional models are technically advanced and aligned with sustainability, transparency, and student agency, echoing organizational learning theory and institutional change models.

One emerging theoretical framework is Digital Sustainability Literacy (DSL). As proposed by Chandran et al. (2023), DSL integrates cognitive, ethical, and ecological domains into digital learning, a critical advancement in defining future-ready quality education. It prepares learners to use digital tools and to evaluate their impact, purpose, and alignment with sustainable values. In tandem, the concept of learning ecosystems reframes educational institutions as adaptive, open systems (Hetch & Crowley, 2020). Learning takes place across platforms, communities, disciplines, and lifespans. Such models reflect the complex education theory, which sees reform not as a linear intervention, but as a co-evolving process across social-technical layers.

These perspectives underscore that quality education must be understood through a systems lens, informed by multi-scalar, cross-sectoral, and interdisciplinary theories that account for the complexity of learning in the Anthropocene. The bibliometric landscape of

this research field supports the emergence of a new theoretical architecture for quality education—one that is digitally-enabled, socially embedded, and ecologically aligned.

Conclusion and Recommendations/Implications

This study offers a comprehensive bibliometric portrait of how global scholarship has approached the intersection of sustainable quality education and technology over the past 15 years. The results underscore that the field has experienced a significant surge in interest, both in volume and thematic complexity, particularly since the onset of the COVID-19 pandemic. The acceleration in publication output reflects a growing acknowledgment of the necessity to reconceptualize education through sustainability lenses and digital transformation. The integration of these two domains has shifted from isolated implementations to more systemic, equity-oriented, and pedagogically grounded models.

A key insight from the findings is that sustainable quality education cannot be defined merely by access to digital tools or infrastructure. Instead, it must be understood as a dynamic system involving pedagogical innovation, policy alignment, socio-cultural adaptation, and ethical considerations. The prominence of keywords such as "equity," "inclusion," "AI," "blockchain," and "eco-pedagogy" suggests that researchers are increasingly focused on understanding how technology can be both an enabler and a disruptor of educational sustainability. The co-occurrence of these terms reveals a new architecture of educational research that demands transdisciplinary approaches and systemic thinking.

Moreover, the significant contribution of countries from the Global South, such as India, Malaysia, and Indonesia, challenges the conventional North-South asymmetries in knowledge production. These countries are adopting and shaping global discourses on sustainable and digital education. However, the findings also show fragmentation in author collaboration networks, indicating a missed opportunity for deeper cross-regional knowledge exchange. Strengthening global research partnerships, particularly South South collaborations, would enhance the richness and relevance of future research in this area.

The study also highlights a need for more integrated theoretical frameworks. While current literature has begun to explore concepts such as Digital Sustainability Literacy, eco-pedagogy, and learning ecosystems, these remain under-theorized and often siloed within disciplinary boundaries. Bridging gaps between educational theory, technological innovation, and sustainability science is crucial. This calls for intentional efforts to promote interdisciplinary academic dialogues, improve teacher education programs, and develop a curriculum that aligns with digital fluency and sustainability literacy.

Regarding practical implications, educational institutions and policymakers should move beyond digital adoption toward digital transformation guided by ethical, inclusive, and ecological principles. This includes infrastructure and human capacity development investments, governance mechanisms, and data-driven quality assurance systems. Educators must be equipped to navigate complex digital ecosystems while fostering learners' critical thinking, civic engagement, and planetary responsibility.

Future research should include qualitative and mixed-method approaches that explore the lived experiences of students and teachers in digitally enabled sustainable education. Bibliometric analysis is a powerful diagnostic tool, but it must be complemented by grounded

research to truly capture the nuanced dynamics of change. Emphasis should also be placed on developing common indicators and metrics to assess sustainability outcomes, thus aligning scholarly efforts to the broader goals of SDG 4 and beyond.

Disclosure statement

The authors declared no potential conflicts of interest.

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