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A Bibliometric Review of Digitalization and Sustainability Interconnection in Smart Campuses Concept development: the ESG Framework Perspective

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ABSTRACT

This study investigates the evolution of research trends at the intersection of digitalization and sustainability within the context of smart campuses. It analyzes how digital innovations impact three core areas of university ecosystems according to the ESG (Environmental, Social, Governance) framework, in particular: environmental management, social engagement, and institutional governance. The research examines 282 peer-reviewed documents through a bibliometric analysis and content review of the 20 most cited studies, identifying the key technologies, sustainability impacts, and conceptual frameworks that have shaped the field over the past two decades. The study demonstrates that smart campuses are becoming digitally driven ecosystems capable of advancing sustainable development goals. Digitalization supports resource optimization, student-centered education, and data-informed governance practices. However, challenges such as digital divides, privacy concerns, and cultural barriers persist. The findings highlight that the successful alignment of smart campus initiatives with sustainability principles requires a systemic, values-based digital transformation strategy development. Therefore, it contributes to the conceptualization of smart campuses as integrated digital-sustainable ecosystems, offering a structured ESG-based framework to guide future academic inquiry, policy design, and practical innovation in higher education institutions.

Questo studio indaga l'evoluzione delle tendenze della ricerca all'intersezione tra digitalizzazione e sostenibilità nel contesto dei campus intelligenti. Analizza come le innovazioni digitali impattano su tre ambiti fondamentali degli ecosistemi universitari secondo il framework ESG (Environmental, Social, Governance), in particolare: gestione ambientale, impegno sociale e governance istituzionale. La ricerca esamina 282 articoli sottoposti a revisione paritaria attraverso un'analisi bibliometrica e una revisione dei contenuti dei 20 studi più citati, identificando le tecnologie chiave, gli impatti sulla sostenibilità e i quadri concettuali che hanno plasmato il campo negli ultimi due decenni. Lo studio mostra che i campus intelligenti stanno diventando ecosistemi guidati dal digitale in grado di far avanzare gli Obiettivi di Sviluppo Sostenibile. La digitalizzazione supporta l'ottimizzazione delle risorse, l'istruzione incentrata sullo studente e le pratiche di governance informate sui dati. Tuttavia, persistono sfide come i divari digitali, i problemi di privacy e le barriere culturali. I

risultati evidenziano che l'allineamento di successo delle iniziative di smart campus con i principi di sostenibilità richiede lo sviluppo di una strategia di trasformazione digitale sistemica e basata sui valori. Pertanto, contribuisce alla concettualizzazione dei campus intelligenti come ecosistemi integrati digitali-sostenibili, offrendo un quadro strutturato basato su ESG per guidare la futura ricerca accademica, la progettazione delle politiche e l'innovazione pratica negli istituti di istruzione superiore.

Keywords: Smart Campus, Sustainability, Digitalization, Digital Transformation, ESG framework

1 – Introduction

With respect to the growing pressure of global challenges, ranging from climate change and resource wastage to social inequality and economic instability, the concept of sustainability has emerged as a guiding principle across all social and economic sectors development, including the sphere of higher education. As key hubs of knowledge production and innovation, higher education institutions (HEIs) face increasing pressure to align their operations and strategies with the principles of sustainable development (Telukdarie & Munsamy, 2019; Giesenbauer & Müller-Christ, 2020; Trevisan, Leal Filho, & Pedrozo, 2024). Within this evolving context, digitalization offers transformative potential, acting both as a critical enabler and as a tool for fostering sustainability-oriented transitions. The interplay between digitalization and sustainability, captured in the emerging concept of "digitainability", highlights not only the parallel significance of these two megatrends but also their synergistic potential, particularly within the HEI landscape (Seele & Lock, 2017; Zang *et al*., 2020; Sepashvili, 2020; Lichtenthaler, 2021; Gazzola *et al*., 2024). One of the most representative displays of such a confluence effect within the educational landscape is generation of the digitally-driven enabling conditions for the sustainable smart campus ecosystem development.

Moreover, digital transformation within the context of HEIs has significantly accelerated over the past decade, reshaping how knowledge is generated, disseminated, and applied, an evolution further amplified by the impacts of the COVID-19 pandemic (Vota, 2021; Treve, 2021; Mospan, 2024). Universities have increasingly adopted Internet of Things (IoT)-based monitoring systems, artificial intelligence (AI)-powered administrative tools, and cloud-based platforms to enhance academic collaboration, campus security, and resource efficiency (Mohamed Hashim, Tlemsani & Duncan Matthews, 2022; Khan *et al*., 2020; Khan *et al*., 2024). These developments have triggered a renewed scientific interest in reconsidering the role of one of the most prominent manifestations of digital transformation in educational environments: the smart campus. This concept refers to a digitally enhanced academic ecosystem that leverages advanced infrastructure and internet-enabled technologies to create interactive, efficient, and secure environments for stakeholder engagement, including students, administrative staff, and municipalities (Mokski *et al*., 2023; Di Gerio & Fiorani, 2024; Wang *et al*., 2024). It reconceptualizes the university as a digitalized value co-creation space, wherein diverse stakeholders interact through digital platforms, enabling data-informed decision-making to improve resource utilization and institutional performance (Aksin-Sivrikaya & Bhattacharya, 2017; Mpofu & Chasokela, 2025).

At the same time, despite increasing adoption of digital technologies, the understanding of how digitalization interacts with the social, economic, environmental, and institutional dimensions of sustainability on campuses remains fragmented (Polin *et al*., 2023). Much of the

existing research tends to isolate the effects of specific technologies, such as IoT or cloud computing, rather than situating digital transformation within a systemic sustainability framework (Sneesl *et al*., 2022; Tyagi, Gupta, & Mehndiratta, 2024). This function-specific focus has limited the development of holistic digital strategies that align with long-term sustainable development goals.

Compounding this issue is the emerging recognition that digitalization, while often positioned as a facilitator of sustainability, is not inherently sustainable. Without deliberate integration, digital tools risk advancing operational efficiency at the expense of ecological and social values. According to recent study introduced by Shajari and David (2025), the growing discourse around the "twin transition" underscores this concern, advocating for a synergistic alignment between digital and green transformations. This perspective emphasizes that digital tools must be strategically designed and governed to mediate, not merely accompany, sustainability transitions. Hence, the prevailing digitainability paradigm, which often assumes a direct correlation between digitalization and sustainability, tends to overlook the unintended consequences of unchecked technological advancement. This simplification underscores the need to reconceptualize digitalization not as an inherent driver, but as a mediating mechanism whose impact on sustainability is shaped by context-specific governance, strategic alignment, and design. Accordingly, further exploration is required to understand how digital transformation can actively moderate and facilitate particular sustainability outcomes within smart campus development processes.

These conceptual limitations are also mirrored in the fragmented legislative and policy frameworks governing sustainable smart campus development. On one hand, smart campuses are increasingly aligned with broader smart city agendas, such as the European Innovation Partnership on Smart Cities and Communities (EIP-SCC) (2012), the Intelligent Cities Challenge (ICC) (2020), and the European Green Deal (2020), which frame technological advancement as a vector for sustainability. On the other hand, sustainable campus initiatives often focus narrowly on the educational domain, emphasizing the integration of sustainability into teaching and research or fostering digital cooperation between HEIs (e.g., the EU GREEN Alliance, European Universities Initiative (2022), EU-CONEXUS Smart Campus (2019), and the European Commission's Digital Education Action Plan, 2021-2027). Moreover, while various smart campus initiatives have been launched worldwide, there remains a notable absence of integrated governance models capable of managing the complex interplay between digital transformation and sustainability (Chagnon-Lessard *et al*., 2021; Polin *et al*., 2023). "Sustainable-smart" campus discourse often lacks a comprehensive understanding of how digitalization aligns with the broader university mission beyond academic delivery. As highlighted by Mahmoud, Hassanain and Alshibani (2024), there is insufficient exploration of how technologies such as AI, IoT, and Building Information Modeling (BIM) can be integrated into facilities management practices to strengthen institutional resilience against environmental and health challenges. This further reflects the fragmented nature of current research and underscores the lack of a comprehensive, systems-based perspective on digital transformation in academic environments.

Hence, in order to consolidate the parallel trajectories of digitalization and sustainability into a coherent and integrated model, it is essential to systematically examine the interdependencies between technological innovation and sustainable development through the lens of the ESG framework. This framework provides a multidimensional perspective for

analysing how digital infrastructures influence environmental performance, social participation, and institutional governance. Within the university context, applying the ESG lens enables a structured assessment of how digital systems and participatory platforms mediate stakeholder behavior, optimize resource use, and support long-term institutional sustainability (Polin *et al*., 2023; Sung & Kim, 2024). Therefore, this study aims to explore how digital transformation supports the advancement of sustainability objectives across university ecosystems by enhancing resource efficiency, stakeholder collaboration, and intelligent infrastructure management, with these effects structured according to the ESG framework. In order to achieve this goal, drawing on the evolving concept of sustainable smart campus as the synergistic integration of digitalization and sustainability within the educational landscape, the research employs a bibliometric analysis of 282 peer-reviewed academic publications to trace the evolution of knowledge in this area. Through a systematic treatment of the bibliometric data, the study identifies the most influential contributions to the field, enabling a critical assessment of existing research patterns and thematic clusters with subsequent disclosure from the ESG perspective based on the systematization of the contributions of the selected set of the most influential studies in the area.

This paper thereby establishes a foundational framework for future research proposing a more integrated understanding of digital transformation not merely as a vehicle for technological advancement, but as a core enabler of sustainability within university settings. The insights generated offer a basis for rethinking traditional campus development paradigms in line with sustainability values, emphasizing human-centric, resilient, and ecologically responsible approaches within the ESG perspective, and underscore the potential of digitainability to redefine sustainability strategies across educational institutions at both academic and operational levels. This perspective opens new agendas for research and policy, encouraging institutions to adopt a more systemic, values-based approach to campus digitalization, and promoting "digitainability" as a guiding principle for the future of higher education.

2 – Methodology and Data

This study adopts a mixed-methods approach combining bibliometric analysis and qualitative content analysis to explore the digital landscape within the smart campus sustainability-driven transition. To conduct a comprehensive literature review at the intersection of campus development, digitalization, and sustainability, it was employed a systematic search strategy using the Scopus database (see Figure 1).

Initially, the search string was formulated as TITLE-ABS-KEY (campus AND digital* AND sustain*) to capture a broad spectrum of studies addressing digital and sustainable initiatives within campus environments, regardless of whether they explicitly used the term "smart campus". The initial query yielded over 400 documents. To enhance the relevance and manageability of the dataset, additional filters were applied: subject areas were restricted to Business, Environmental Science, Social Sciences, Economics, and Computer Science, reflecting the multidisciplinary nature of the topic. The final dataset consists of 282 peer-reviewed studies retrieved from Scopus, covering the publication period from 2004 to 2024. Document types were narrowed to articles, conference papers, and book chapters to focus on scholarly contributions, and only documents published in English were included to ensure accessibility and consistency.

The bibliometric analysis was carried out using the Bibliometrix R-package in conjunction with its web-based interface, Biblioshiny. This methodological framework enabled the systematic examination of core indicators, including annual publication trends, leading authors and institutions, source influence, highly cited works, and co-occurrence patterns among keywords (Ellegaard & Wallin, 2015; Donthu *et al*., 2021).

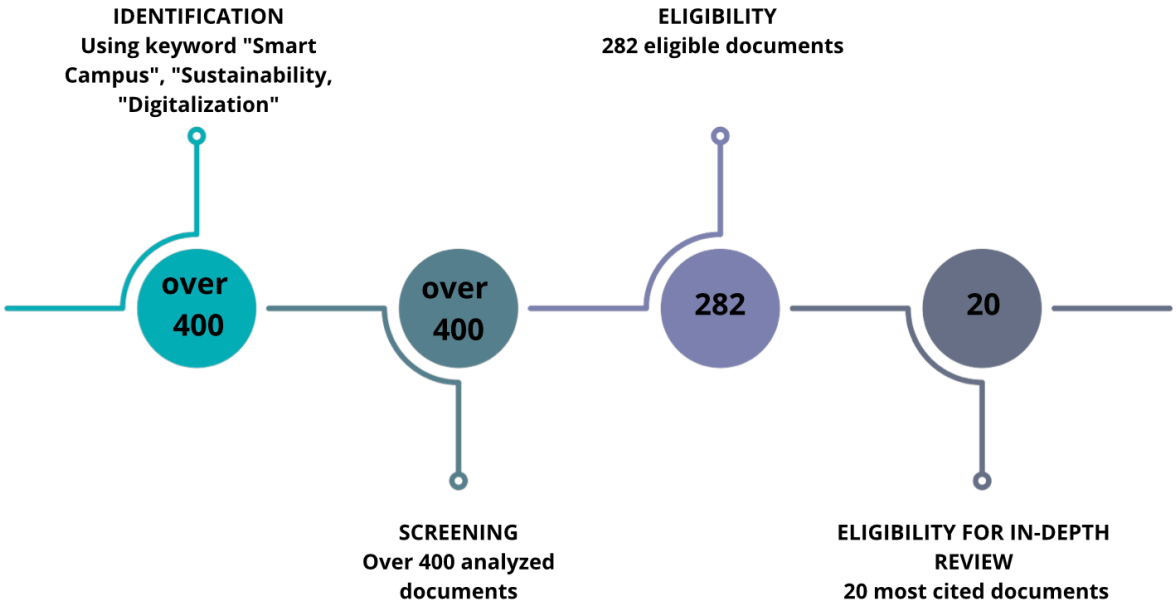

Fig. 1 – Diagram process (Source(s): Author's own elaboration**)**

This helped map the intellectual structure and thematic evolution of smart campus research. Finally, a qualitative content analysis was performed on the 20 most cited papers identified through the bibliometric phase. Within this stage the selected set of papers was analyzed from the standpoint of smart campus framework conceptualization, prioritized sustainability dimensions, classified according to ESG indicators, and emphasized specific digital technologies such as IoT, digital twins, AI, and cloud platforms. Attention was given to the roles of various stakeholders (students, faculty, administrators), the challenges faced (policy constraints, funding limitations, infrastructural barriers), and the contributions toward Sustainable Development Goals (SDGs).

Through the ESG lens, the qualitative analysis further mapped how digitalization efforts in smart campuses are interconnected with sustainability strategies, drawing out patterns of convergence and divergence across environmental efficiency, social well-being, and governance innovation. This integrative approach facilitated a comprehensive examination of the multifaceted contributions of smart campuses to sustainable development, offering a critical synthesis of dominant conceptual models, identified challenges, and emerging strategic pathways as reflected in the current scholarly discourse.

3. Analysis and results

In this study, a comprehensive bibliometric analysis of smart campus research from 2004 to 2024 was conducted, covering 282 documents authored by 934 individuals (Liu *et al*., 2023; Raman & Suresh, 2022). The field displays notable diversity, reflected by 1,014 distinct author keywords

and contributions from 213 sources (Nyoman Sedana, 2015; Schreiber *et al.*, 2021). Collaboration dominates, with an average of 3.5 co-authors per document and 12.41% of publications featuring international collaboration, while 46 documents were single-authored (Jiang *et al.*, 2024; Al-Tammemi *et al.*, 2022). The data also reveal a highly dynamic and evolving research area, with an average document age of 4.94 years and an impressive annual growth rate of 22.19% (Lafferty & Roberts, 2022). The significance of this academic production is underscored by an average citation rate of 9.688 citations per document, demonstrating the growing influence of smart campus studies (Mune *et al.*, 2015; Mohamed *et al.*, 2020) (see Figure 2).

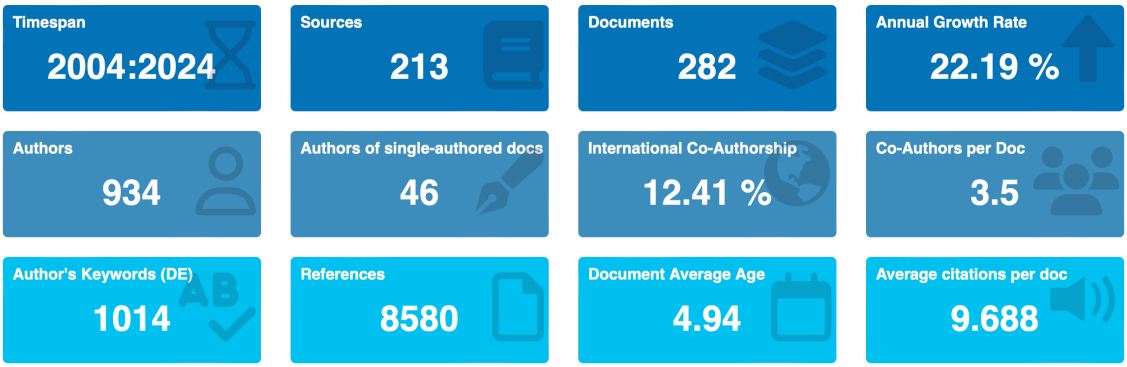

Fig. 2 – Generalized statistics using Bibliometrix and R studio (Source(s): Author's own elaboration**)**

Examining the annual scientific production (see Figure 3), it is evident that scholarly interest was modest and fluctuating between 2004 and 2015, reflecting the early stages of research into campus digitalization and sustainability (Mangiarotti, Paoletti, & Morello, 2008; Bessant, 2014).

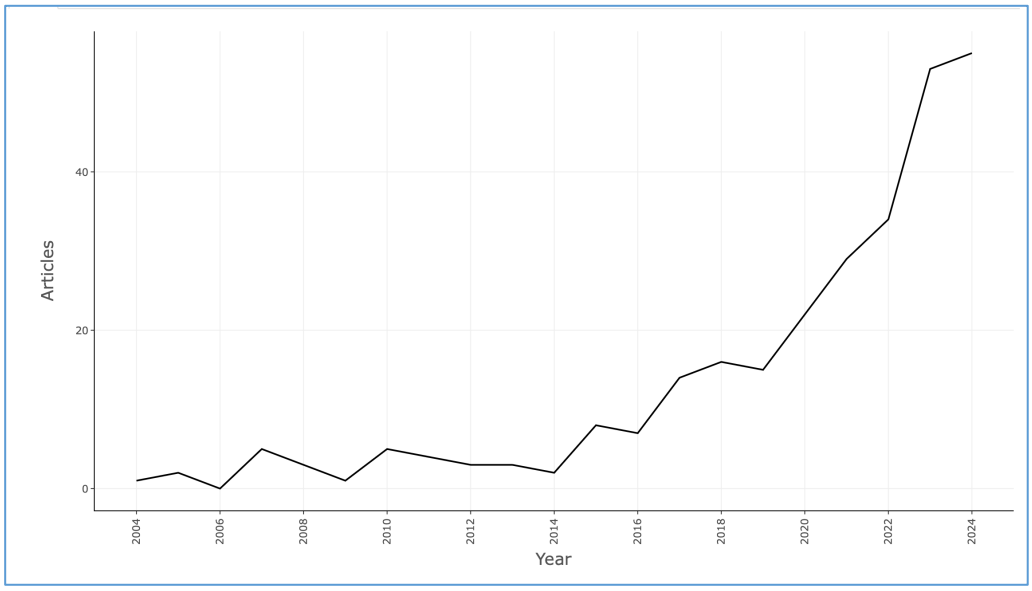

Fig. 3 – Annual scientific production using R-Studio and Bibliometrix (Source(s): Author's own elaboration**)**

From 2016 onwards, a more consistent growth is visible (Dayananda, Jayasuriya, & Fransson, 2017; Byrd, 2018), which accelerated dramatically after 2020 due to the pandemic-

driven shift to remote education, smart infrastructure adoption, and the stronger institutional alignment with SDGs (García-Aranda *et al*., 2024).

The sharp rise in publications through 2023 and 2024 highlights the consolidation of smart campuses as a crucial research domain where digital transformation and sustainability converge, opening new pathways for higher education innovation and societal impact (Ray *et al*., 2024; Lewlomphaisarl *et al*., 2023). Subsequently, the analysis develops a deeper understanding of the citation dynamics within the smart campus research domain. Figure 4 visualizes the evolution of average citations per year.

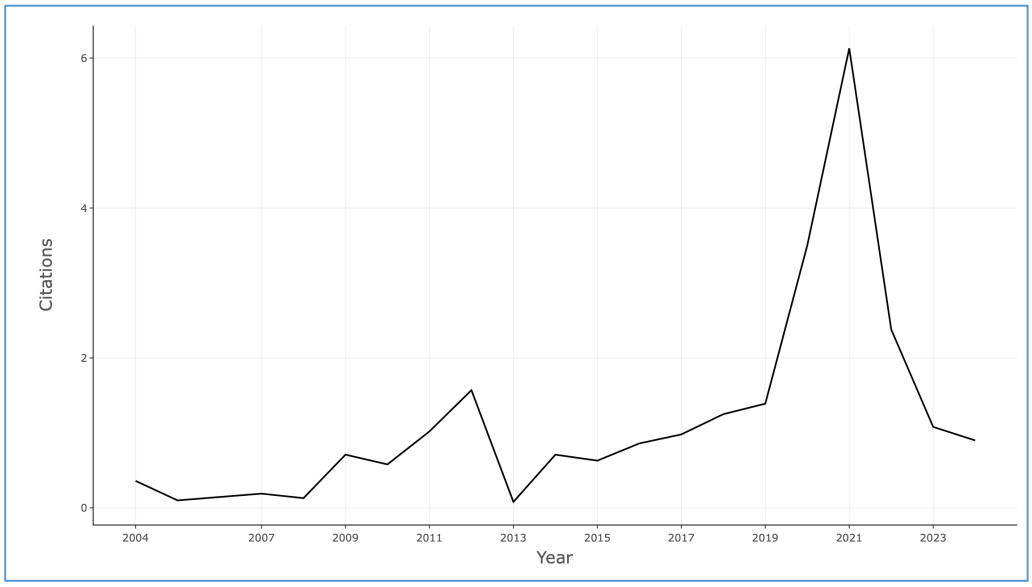

Fig. 4 – Average citation per year using R-Studio and Bibliometrix (Source(s): Author's own elaboration**)**

The data reveal that research on smart campuses remained relatively low in citation impact from 2004 to around 2016, with only sporadic increases (Griffiths, 2008). However, starting from 2017, a steady rise is observed, culminating in a remarkable peak in 2021 (Badilla-Quintana & Sandoval-Henríquez, 2021; Martínez *et al*., 2021). This suggests a growing academic and practical interest in the intersection between digitalization, sustainability, and campus development, likely accelerated by global challenges such as the COVID-19 pandemic and increasing policy pressures towards sustainability goals. After 2021, a slight decline appears, possibly due to the recency of publications in the last years which have not yet accumulated citations (Dwivedi *et al*., 2024; McGrath, 2023). This trend highlights a dynamic, maturing field gaining momentum within the broader sustainability and higher education contexts.

Another important dimension of the analysis concerns the dissemination channels of smart campus research. Figure 5 presents the top 10 sources ranked by the number of documents published.

Notably, the journal *Sustainability (Switzerland)* stands out with 16 documents, indicating its pivotal role in promoting studies linking digital innovations and sustainable practices in university campuses (Silva-da-Nóbrega, Chim-Miki, & Castillo-Palacio, 2022; Lindemann-Matthies, Heber, & Remmele, 2024). Following this, sources like the *ACM International Conference Proceedings Series* (Wang *et al*., 2022) and *IOP Conference Series: Earth and Environmental Science* (Kamaruddin *et al*, 2024) also demonstrate significant contributions, emphasizing the

multidisciplinary and technological orientation of the research field. The presence of journals such as *World Sustainability Series* and *Smart and Sustainable Built Environment* underlines the cross-sectoral nature of smart campus discussions, bridging environmental science, education technologies, and sustainability management (Wolff, 2019).

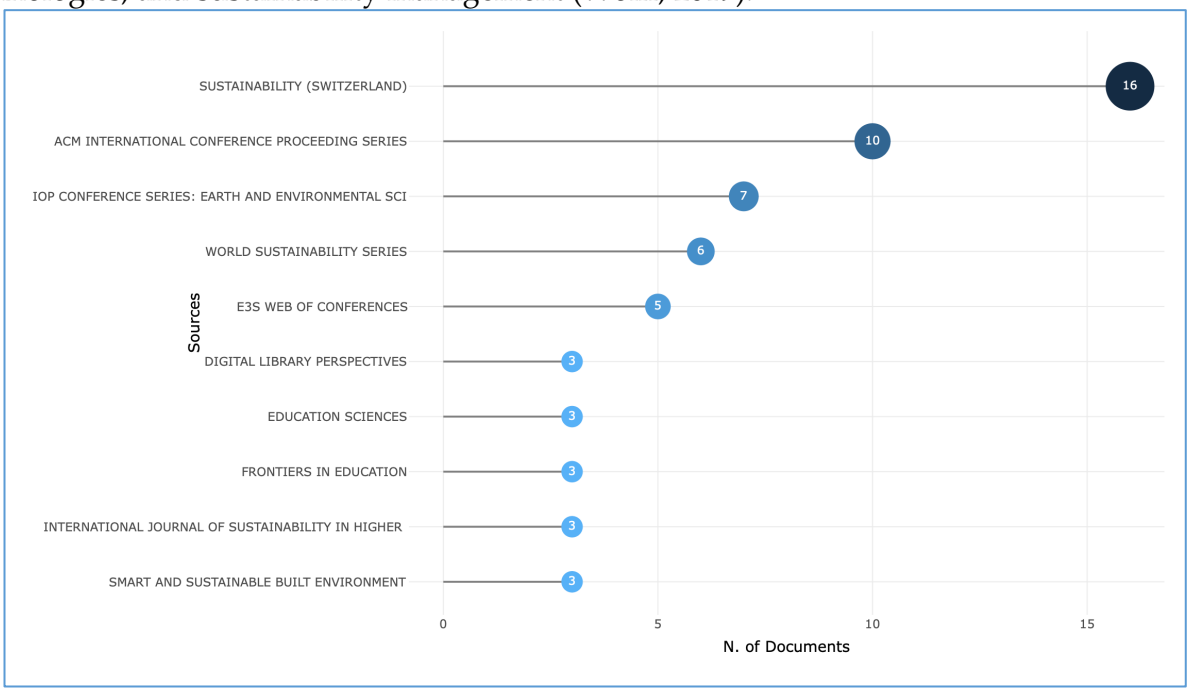

Fig. 5 – Most relevant sources using R-Studio and Bibliometrix (Source(s): Author's own elaboration**)**

Reviewing the Corresponding Author's Countries graph (see Figure 6), it becomes clear that the United States and China lead in research output with the highest number of documents (Reffat, Wadie, & Yousef, 2024; Longmeier & Murphy, 2021), followed closely by Australia.

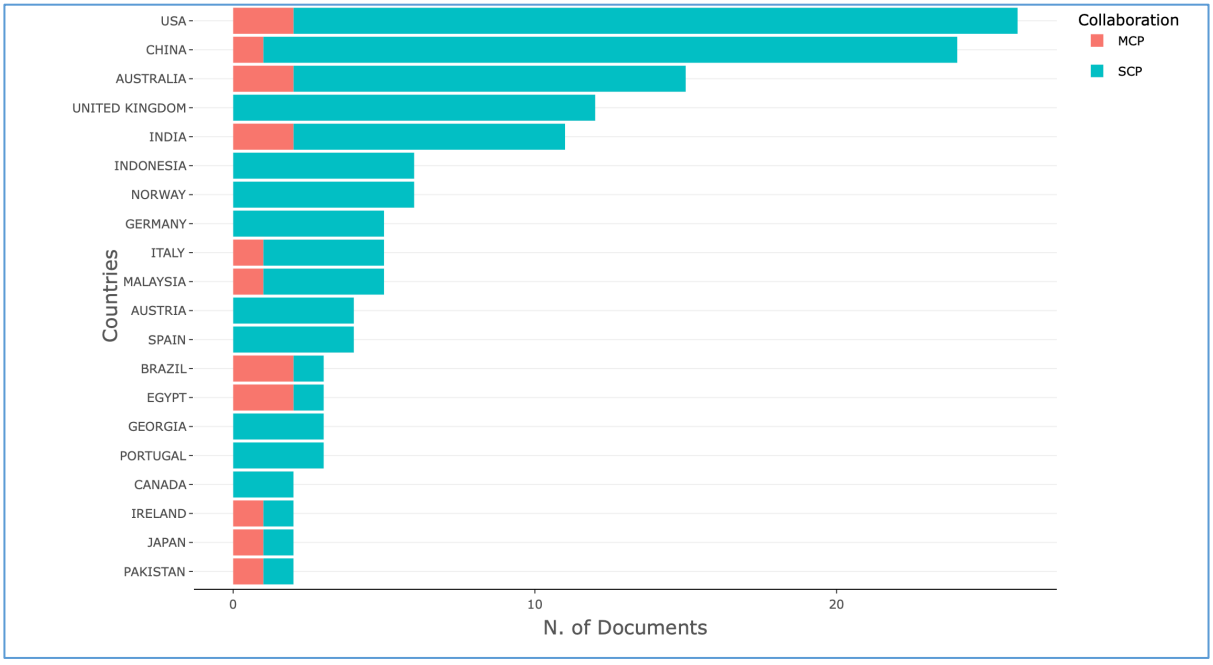

Fig. 6 – Corresponding author's countries using R-Studio and Bibliometrix (Source(s): Author's own elaboration**)**

The United Kingdom, India, and Indonesia also demonstrate strong engagement, highlighting a diverse and international scholarly community (Littlejohn *et al*., 2021; Kamaruddin *et al*., 2024). This distribution reveals a global research ecosystem with North America, Asia, and Europe prominently driving the smart campus agenda. Notably, the collaboration index, as seen from the distinction between single-country publications (SCP) and multiple-country collaborations (MCP), shows that the United States and China maintain a higher level of domestic research output compared to other countries, though international collaborations are also relevant. Countries such as Norway, Germany, and Italy demonstrate a balanced output between national and cross-border research activities, aligning with broader trends of European academic integration (Lindemann-Matthies, Heber, & Remmele, 2024). The data reveal that while developed nations dominate the field in terms of volume, emerging economies such as Indonesia and Malaysia are progressively contributing, driven by the need to modernize educational infrastructures and achieve SDG (Bakar *et al*., 2024).

These findings illustrate a dynamic and geographically diverse research landscape, where innovation in smart campus models increasingly transcends national boundaries, fostering knowledge exchange across different educational and technological ecosystems.

To visualize the structural relationships within the smart campus research domain, a three-field plot was generated using R Studio based on 282 Scopus-indexed publications from 2012 to 2023. This type of bibliometric visualization allows for the simultaneous representation of three interconnected dimensions of scholarly production. In this case, the fields are: sources (journals or conference proceedings) on the left, countries of authorship in the center, and keywords on the right. The thickness of the connecting lines (edges) between fields represents the frequency or intensity of co-occurrence among the items, offering an intuitive overview of which countries publish in which journals and which themes are most commonly associated with their work.
As shown in Figure 7, The central column of the plot clearly shows the United States as the most active contributor to smart campus research, followed by Australia, Italy, China, and India.

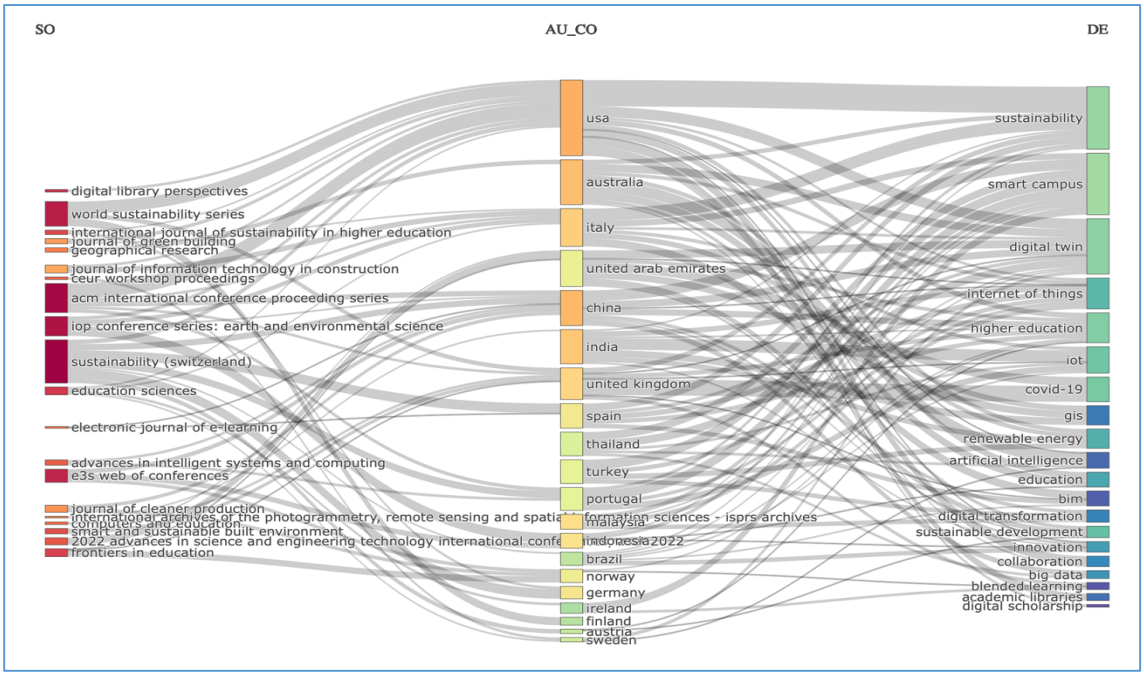

Fig. 7 – Three Field Plot using R-Studio and Bibliometrix (Source(s): Author's own elaboration**)**

This global distribution indicates that smart campus development is not localized but rather reflects a globally shared interest in the digital transformation of higher education environments. For instance, Li (2022) analyzes the shift to online education in China using smart campus tools, while Phanichsiti *et al*. (2023) discuss the role of IoT and big data in the sustainability of smart campuses in Thailand. On the left side of the graph, the most frequently used publication sources include the ACM International Conference Proceeding Series, Education Sciences, and Sustainability (Switzerland). These reflect the interdisciplinary nature of the topic, which spans fields such as information technology, education policy, urban studies, and sustainability science. The integration of digital gamification into physical campus environments demonstrates the blending of technical and behavioral dimensions in smart campus initiatives. The right-hand column of the three-field plot reveals the most prominent research keywords, with "smart campus" centrally linked to terms such as "sustainability", "digital twin," "Internet of Things", "higher education", and "COVID-19".

These co-occurrences reflect a broader research agenda in which smart campuses are understood as digitally enhanced ecosystems designed not only for operational efficiency but also for social and environmental impact (Poe, 2022). The presence of terms like "blended learning" and "digital libraries" highlights the post-pandemic acceleration of educational digitalization, while "artificial intelligence" and "big data" point to emerging trends that are increasingly shaping campus design and governance. In summary, the three-field plot provides a multi-dimensional overview of the research landscape, linking publication venues, geographic authorship, and conceptual focus. It not only maps the interdisciplinary and international scope of the smart campus discourse but also helps to identify key thematic clusters and underexplored connections, serving as a valuable tool in bibliometric and scientometric analysis.

The subsequent step investigates cooperation among countries, visualized in Figure 8.

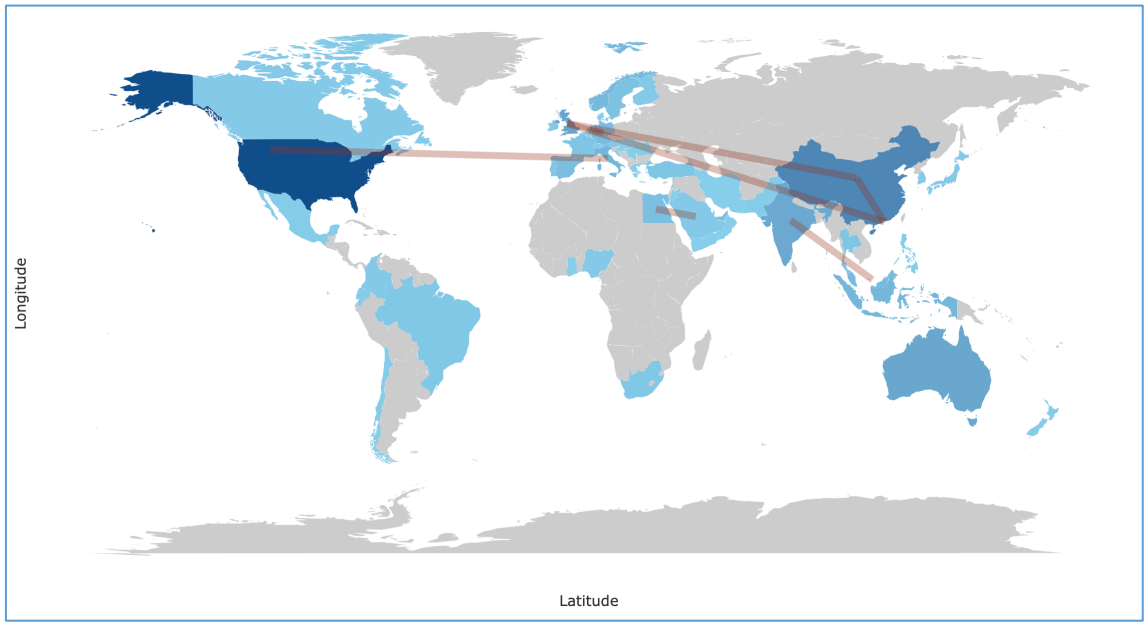

Fig. 8 – Cooperation among countries using R-Studio and Bibliometrix (Author's own elaboration**)**

The world map showcases a network of active collaboration pathways, primarily connecting North America, Europe, and Asia. Strong collaboration ties between the USA and countries such as China, Australia, and European nations are particularly visible, indicating that the discourse around smart campuses is not confined to isolated national efforts but thrives through international partnerships (Gómez-Carmona *et al*, 2022).

These connections underscore the importance of collective global initiatives in advancing digitally and sustainably oriented campus environments, reinforcing how global academic collaboration is crucial for building integrated smart campus systems aligned with SDGs.

Finally, the last analysis, presented in Figure 9, investigates the co-occurrence of keywords, offering insights into the intellectual structure of the research field.

The network visualization highlights *"sustainable development"* as the most dominant term (Abakumov & Beresten, 2023), closely linked to concepts such as *"digital storage"*, *"internet of things"*, and *"students"* (Gómez-Carmona *et al*, 2022). Other notable clusters emphasize *"higher education institutions"*, *"e-learning"*, and *"renewable energy"*, suggesting that research not only focuses on technical innovation but also on institutional transformation and educational outcomes (García-Aranda *et al*., 2023; Silva-da-Nóbrega, Chim-Miki, & Castillo-Palacio, 2022).

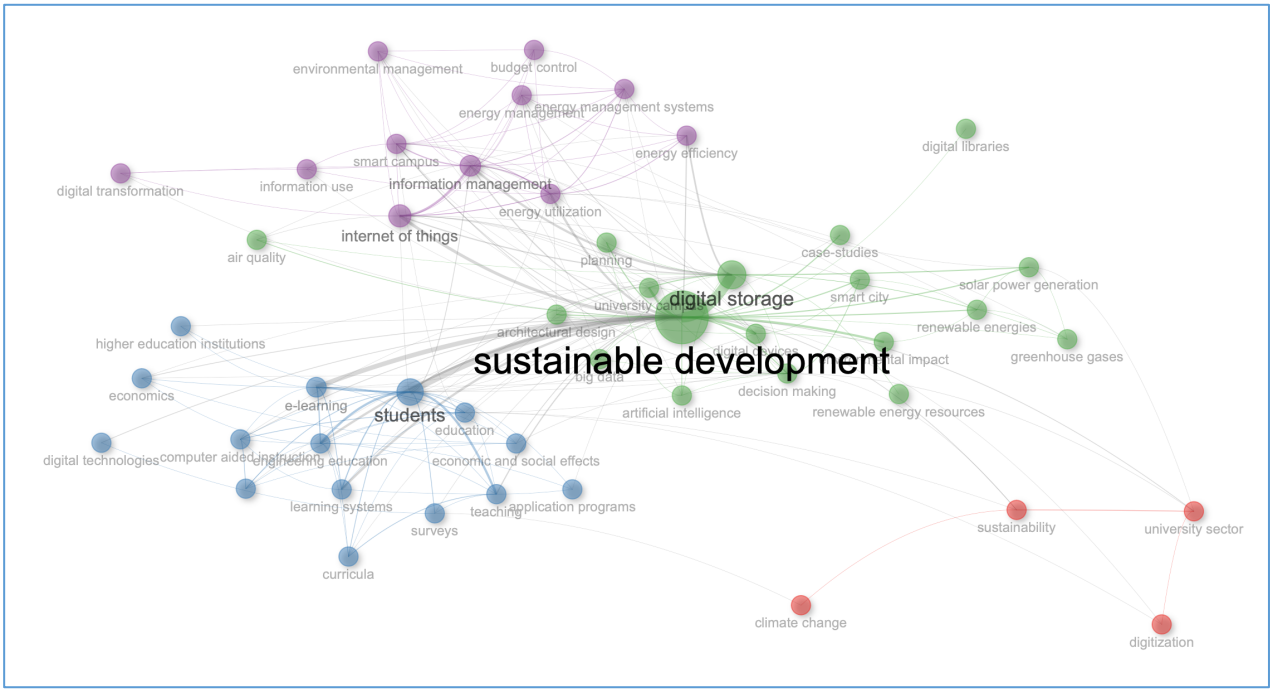

Fig. 9 – Networked keywords using R-Studio and Bibliometrix (Source(s): Author's own elaboration Author's own elaboration)

The keyword network illustrates the convergence of environmental, educational, and technological priorities, reinforcing that digital innovation is deeply interwoven with sustainability imperatives in the evolution of smart campuses. Around this core, several thematic clusters emerge. One prominent cluster, dominated by terms such as *"students"*, *"e-learning"*, *"education"* and *"higher education institutions"*, reflects the strong pedagogical dimension of the field (Bakar *et al*., 2024; Al-Tammemi *et al*., 2022). This cluster illustrates how digitalization strategies are deeply intertwined with efforts to enhance student learning experiences, foster inclusivity, and modernize academic programs through smart technologies. Another major cluster revolves around *"digital storage"*, *"information management"*, and the

"*Internet of Things*". This technological cluster emphasizes the importance of data infrastructures, real-time connectivity, and smart devices in enabling the operational aspects of smart campuses (Pexyean, Saraubon, & Nilsook, 2024; Pexyean, Saraubon, & Nilsook, 2022). The proximity between "*information management*" and environmental concepts like "*energy management*" and "*energy utilization*" highlights the role of digital systems in supporting energy efficiency and resource optimization strategies (Dahlan *et al*., 2022). A smaller but distinct cluster focuses on "*sustainability*", "*climate change*", and "*university sector*", suggesting a line of research concerned with how institutional policies and campus management practices can contribute to environmental stewardship at a systemic level (Geh, Emuze & Das, 2023; Tumedei, Ceccarini, & Prandi, 2024). The network structure also reveals bridges between clusters, with terms like "*decision making*", "*artificial intelligence*" and "*smart city*" acting as connectors. These bridging terms indicate that the field increasingly acknowledges the necessity of integrating intelligent decision support systems and urban-scale perspectives into campus planning and management (García-Aranda *et al*., 2024). Overall, the co-occurrence network portrays a rich and interconnected intellectual landscape where digital technologies, educational transformation, and sustainability imperatives converge. The structure suggests that the future of smart campus research will likely depend on the further integration of technical, pedagogical, and environmental dimensions, fostering holistic innovation in higher education ecosystems.

The thematic map of Smart Campus Research visually organizes the main research themes on smart campuses based on their development (density) and relevance (centrality). Motor themes are well-developed and crucial to the field, while basic themes are essential but less structured. Niche themes are specialized yet peripheral, and emerging or declining themes reflect areas of new growth or reduced interest. Built from the co-occurrence of keywords across 282 articles, the map highlights both consolidated research areas and emerging directions in smart campus studies. The thematic map depicted in Figure 10 provides a strategic overview of the conceptual structure and maturity of research themes in the smart campus domain.

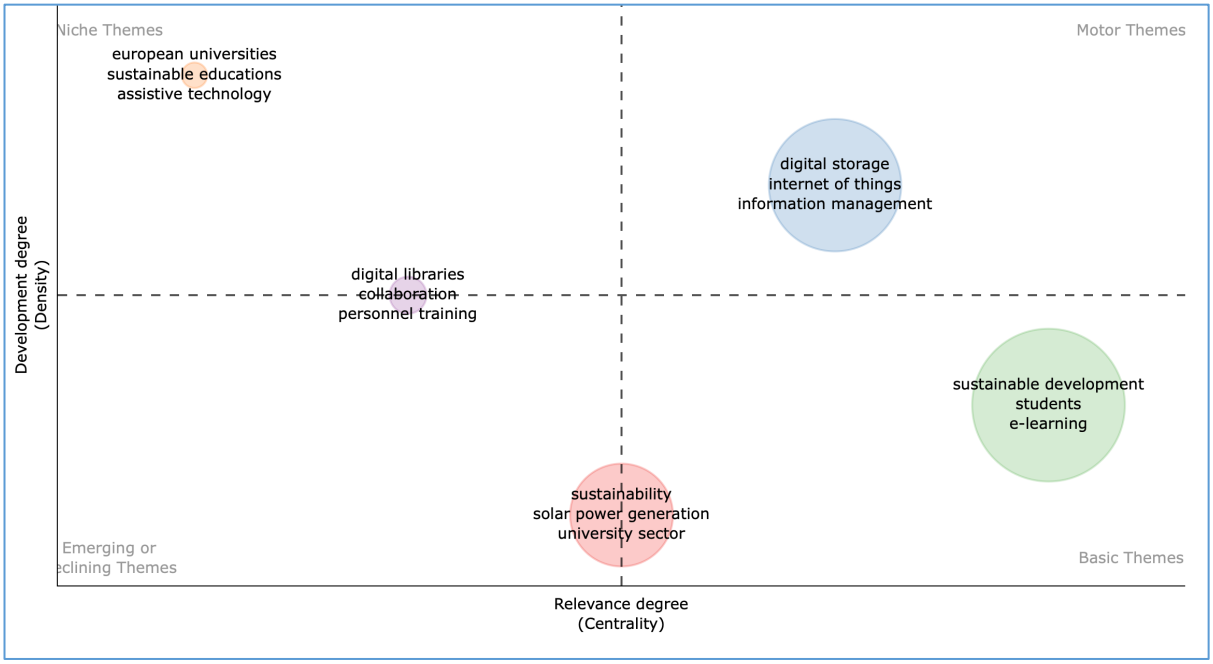

Fig. 10 – Thematic Landscape of Smart Campus Research using R-Studio and Bibliometrix
(Source(s): Author's own elaboration)

The map categorizes themes based on their degree of development (density) and relevance (centrality), offering insight into the intellectual organization and future trajectories of the field.

The *Motor Themes*, positioned in the upper-right quadrant, are characterized by both high centrality and high density, indicating well-developed and highly connected areas of research. In this case, "*digital storage*", "*Internet of Things*" and "*information management*" form the core drivers of smart campus innovation (Curralo *et al*., 2022; Pexyean, Saraubon, & Nilsook, 2023). These themes underpin the technological infrastructure required for real-time monitoring, data-driven decision-making, and sustainable management practices across campus operations.

The *Basic Themes*, found in the lower-right quadrant, such as "*sustainable development*", "*students*" and "*e-learning*", represent essential but less internally complex areas. These topics are fundamental to the smart campus discourse, providing broad, stable foundations that link technological transformation with educational and sustainability goals. Their position suggests that while they are central to the research field, their conceptual structures are still evolving and offer ample opportunities for deepening and specialization (Silva-da-Nóbrega, Chim-Miki, & Castillo-Palacio, 2022; Chiu, 2023).

In the Emerging or Declining Themes quadrant (lower-left), we find "*sustainability*", "*solar power generation*", and "*university sector*". These topics currently exhibit lower density and centrality, indicating either nascent areas of research that have yet to consolidate or mature fields that may be losing relative prominence (Buck *et al*., 2023; Elshapasy & Mohamed, 2024). Their presence highlights the necessity for renewed efforts to integrate energy transition strategies and broader sectoral transformations into the smart campus discourse.

Finally, the Niche Themes in the upper-left quadrant, such as "*European universities*", "*sustainable educations*", and "*assistive technology*", are highly developed but relatively isolated. These areas often involve specialized applications, pilot programs, or regionalized projects that, while internally cohesive, have yet to fully permeate the broader field (Bakar *et al*., 2024; Lamb, 2024).

Overall, the thematic map reveals a maturing research landscape where technological innovation, sustainable development, and educational transformation intersect dynamically. The clear emergence of data management and IoT as motor themes suggests that future research will increasingly focus on refining the digital backbone of smart campuses, while sustained attention to student-centered and sustainability-driven initiatives will be critical for ensuring broader societal impact.

Finally, the analysis of trend topics, as illustrated in Figure 11, highlights the evolving nature of research priorities in the smart campus, sustainability, and digitalization domains over the past decade.

Early research, beginning around 2011–2015, focused primarily on foundational themes such as "*education*", "*computer-aided instruction*", and "*digital libraries*", reflecting an initial emphasis on digitizing educational processes and improving digital information management within higher education environments (Lee, 2022; Wang *et al*., 2024).

As the field progressed, from 2016 onward, a second wave of concepts emerged, centered around "climate change", "application programs", "surveys" and "learning systems" (Schöpfel, 2017; Amma, Shafeek, & Viswambharan, 2018). These topics indicate a broadening of scope beyond purely technological upgrades, towards the integration of environmental concerns and more sophisticated academic program development strategies. From 2018 onward, more complex and integrated topics, including "higher education", "smart city", and "students",

began to gain prominence (Bäcklund, Lundqvist, & Molinari, 2024; Ashmarina & Nikulina, 2017).

This shift marks a key transition point where the smart campus began to be conceptualized not just as a collection of isolated technologies, but as an interconnected system within a larger urban and societal ecosystem. In the most recent years, particularly from 2020 to 2024, the field has experienced a clear convergence around sustainability-driven and technology-enabled frameworks.

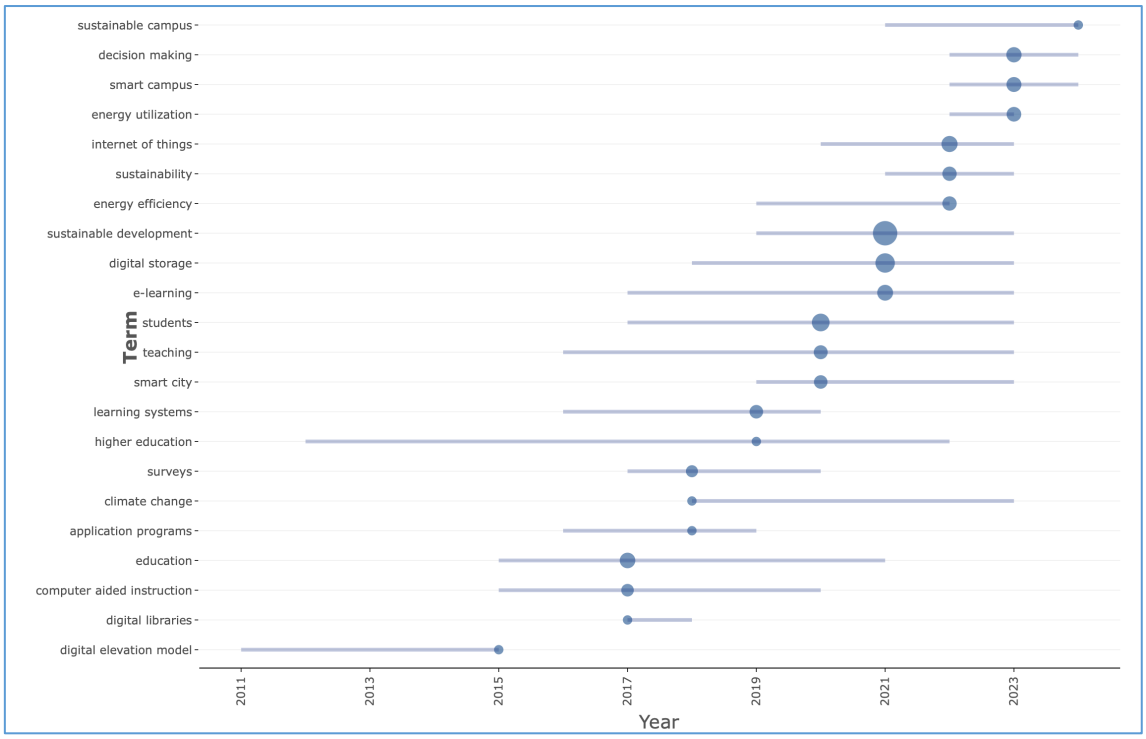

Fig. 11 – Emerging and Evolving Topics in Smart Campus Research using R-Studio and Bibliometrix (Author's own elaboration)

Concepts such as "sustainable development", "energy efficiency", "internet of things", "smart campus", "decision making", and "sustainable campus" dominate the thematic landscape (Alvarez *et al*., 2024; Pexyean, Saraubon, & Nilsook, 2022; Emblen-Perry *et al*., 2016). Their temporal trajectories show a rapid acceleration, signaling an increased urgency to link digital transformation efforts with ESG goals within university operations (Zaballos *et al*., 2020). The emergence of terms like "energy utilization" and the continued importance of "e-learning" and "digital storage" demonstrate how operational and educational dimensions are now deeply intertwined in contemporary smart campus strategies (Schreiber *et al*., 2021). The intersection between data management, sustainability goals, and real-time decision support systems has become a core driver of innovation across higher education institutions. Overall, this updated trend analysis confirms that smart campus research has evolved from early technological experimentation toward comprehensive, system-oriented approaches. Current and future developments clearly align with global digital transformation priorities and sustainability challenges, suggesting a rich and dynamic field poised for continued interdisciplinary expansion.

4 – Analysis of the most cited papers

Finally, this review discloses the role of digital transformation in smart campus development introducing ESG framework based through the content analysis of the 20 most cited papers, exploring the deployment of the advanced digital technologies to reach the sustainability-related outcomes with respect to the environmental, societal and governmental indicators. The categorization approach draws on conceptual synthesis techniques used in bibliometric literature reviews (Tranfield, Denyer, & Smart, 2003) and on methodologies for clustering different research focus by thematic convergence (Donthu *et al*., 2021). Table 1 maps the selected studies align with these three conceptual avenues. It emphasizes the generalized focus of the studies and summarizes the sets of core digital technology infrastructures considered in the frame of each category.

This provides a structured basis for the subsequent conceptual synthesis of ESG-framed smart and sustainable campus development implications.

4.1 – *Digital transformation and sustainability outcomes for smart campus: environmental indicators*

The studies, adhered to this category, consider the digital transformation as a significant toolkit aimed to enhance the environmental sustainability of smart campus initiatives by offering a digital landscape through which universities can monitor, assess, and reduce their ecological footprints. Its core focus - deployment of IoT networks, digital twins, data-driven architectures, and integration of smart systems as primary drivers of campus innovation – according to the Table 1, is considered within two generalized technologically-conditioned directions:

(1) *Smart infrastructure tools and resource saving strategy*. The deployment of IoT-based tracking systems, smart waste bins, and digital environmental monitoring platforms facilitates efficient waste segregation, collection, and recycling. This, in turn, directly enhances waste generation and diversion rates as a key environmental performance indicator. According to Zaballos *et al*. (2020), campus digital twin platform, utilizing real-time IoT sensing and building information modelling to monitor indoor comfort and energy use, provides facility managers with actionable insights.

Hence, the integration of Information and Communication Technologies (ICT), wireless sensor networks, and digital twins enables real-time resource monitoring and data-driven decision-making, while also fosters environmentally oriented behavioural adjustments. (Yang *et al*., 2020). For instance, introduction of IoT- and cloud-enabled smart classroom systems through optimized real-time resource management provides an adaptive learning ecosystem (Revathi, Suganya & Gladiss Merlin, 2020). Moreover, the digitalization of campus operations fosters a culture of sustainability by promoting behavioural change among students and staff, encouraging energy-saving behaviours and waste reduction practices. This behavioural shift can be monitored and evaluated using participation rates in sustainability programs, per capita resource use, and environmental awareness indices. Therefore, deployment of such digital technologies provides contribution to the energy and water consumption reduction as well as carbon emissions optimization, aligning smart campus operations with internationally recognized indicators, such as GHG (greenhouse gas) emissions per capita, energy intensity, and renewable energy utilization rates (Ebrahimi & North, 2017; Martins *et al*., 2021; Martínez

et al., 2021).

(2) *Life cycle assessment and planning tools.* Advanced environmental infrastructures, including BIM and cloud-based data analytics, support continuous monitoring of indoor environmental quality, thermal comfort, and air pollutant concentrations (e.g., PM2.5, CO_2 levels). These systems contribute to enhancing health-related sustainability metrics (Horn *et al*., 2020). Additionally, microclimate modelling tools facilitate the mitigation of the urban heat island (UHI) effect and the enhancement of passive design strategies, resulting in more energy-efficient building layouts and improved building envelope performance. In turn, Life Cycle Assessment (LCA) tools, being integrated with smart urban planning models, enable universities to assess and minimize the embodied carbon and material intensity associated with construction, maintenance, and demolition activities (Zou *et al*., 2024; Huang *et al*., 2018). This contributes to reductions in construction-related emissions and non-renewable material consumption as critical indicators in evaluating environmental impact over the full campus infrastructure lifecycle.

Therefore, the environmental impact of such technological frameworks is significant with respect to its potential to reinforce environmental sustainability, optimizing resources consumption and enhancing building strategies. For instance, Xiao (2019) in the study critiques Chinese universities' strategic plans, pointing out the missed opportunity to embed sustainability directly into digitalization efforts. In such a way, digital transformations support universities in advancing environmental sustainability goals in alignment with the SDGs, in particular SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Table 1 – ESG structuring of top 20 most cited documents on smart campus

ESG framing	Focus	Digital tools
Environment		
– Smart Infrastructure and resource saving strategy; **– Lifecycle Assessment and Planning Tools**	• *Application of IoT, sensors, digital twins, and architectural frameworks for sustainable, efficient campus environments.* • *Incorporation of digital models and data to inform design, planning, and long-term campus sustainability*	• Core digital infrastructures and data platforms: cloud integration, Big Data platforms, streaming data platforms, Edge computing, wireless sensor networks, cloud-based campus portals, unified campus management systems (Martinez *et al*., 2021). • Smart campus monitoring and management technologies: smart energy systems, water and energy smart management systems, energy efficiency tracking systems, smart resource optimization applications, smart readiness indicators (SRI) systems, environmental monitoring sensors, digital microclimate simulation platforms (e.g., MATLAB), digital elevation models (DEM) for structures and data platforms: campus planning (Yang *et al*., 2020). • IoT and smart services for campus life: IoT classrooms, student behaviour monitoring through IoT, campus living labs for IoT testing, surveillance technologies, smart tech for resource tracking (Revathi *et al*., 2020; Simmhan *et al*., 2018). • Collaborative and learning technologies: online classroom systems, remote learning and e-learning infrastructures, collaborative digital platforms, peer support via messaging apps, Service-oriented architectures (SOA) (Martins *et al*., 2021). • Modelling, and strategic management tools: cross-sector collaboration frameworks, AI-based decision-making systems for sustainability, building information modelling (BIM), digital life cycle assessment (LCA) tools, information delivery manual (IDM) systems, model view definition (MVD) based planning tools, integrity technologies (Huang *et al*., 2018. (Xiao, 2019) Horn *et al*., 2020. • Advanced simulation and innovation tools: digital twins, microclimate modelling (Yao *et al*., 2011; Zaballos *et al*., 2020)
Social		

– Digital learning transformation; **– Sustainable service delivery (transparency of the processes, etc.)**	• *Potential of digital tools and platforms to reshape teaching and learning models*	• Digital learning platforms and infrastructures: E-learning systems, online classroom environments (asynchronous and synchronous), virtual campus infrastructures, distance education models, blended-learning models (online and campus - OaC model), cloud-based storage for educational resources (Petronzi & Petronzi, 2020) (Watermeyer *et al*., 2021); • Teaching and content delivery tools: digital lecture streaming, video repositories, video conferencing platforms, online assignment submission and grading systems, digital tools for flexible, self-paced learning. (Littlejohn *et al*., 2021); • Student engagement and support technologies: peer support via messaging apps and forums, digital learning communities, threaded discussion platforms, smart campus unified portals, institutional support portals for student services, online student engagement and monitoring systems. (Li, 2022). • Collaborative learning and groupwork tools: digital collaborative platforms, shared document co-authoring tools, gamified learning environments, augmented reality (AR) mobile games, Printed game-based learning alternatives (Lee, 2022). • Smart and IoT-enabled educational tools: real-time attendance tracking via IoT devices, microcontroller-based educational hardware (IoT kits), smart scheduling and time-management apps for students (Timmis, 2012). • Data-driven education technologies: learning analytics platforms, online assessment and examination tools, remote learning infrastructures, cloud integration for education. (Anderson & Rivera Vargas, 2020).
Government		
– Institutional and behavioural sustainability	• *Potential of digital technologies to the reshape governance dynamics and ethics*	• Digital governance frameworks and collaborative learning and groupwork tools: online exam proctoring systems, instant messaging platforms, collaborative digital learning networks, green offices (GO model), peer-to-peer digital training programs, digital platforms for sustainability campaigns, online learning management systems (LMS), digital surveys and data collection tools (Adomßent *et al*., 2019; Silva-da-Nóbrega *et al*., 2022; Selwyn *et al*., 2023).

4.2 – *Digital transformation and sustainability outcomes for smart campus: societal indicators*

The reviewed studies examine the transformative potential of digital tools and platforms in reshaping HEIs to align it with a broader societal shift toward technology-driven educational models. Such a shift is characterized as a digital learning transformation from the perspective of sustainable service delivery, including process transparency improvements (see Table 1). These researches underscore both the opportunities and constraints associated with this transition. For example, Watermeyer *et al*. (2021) and Li (2022) highlight the ambivalent effects of online learning, recognizing its potential to increase student flexibility while also exposing challenges related to mental health and emotional resilience.

The transition to digital platforms, which was accelerated during the COVID-19 pandemic, has underscored critical social sustainability challenges, particularly concerning ethical, psychological, and equity-related dimensions (Petronzi & Petronzi, 2020; Littlejohn *et al*., 2021). The implementation of digital education tools, such as online learning management systems, surveillance software for academic integrity, and remote proctoring technologies, has raised pressing concerns about student privacy, data protection, and the psychological impacts of digital surveillance. These concerns highlight the need to balance institutional accountability with student autonomy and trust as core elements of a socially sustainable digital campus. The migration to online education, the proliferation of mobile learning platforms, and peer-support communities have expanded educational access and resilience capacities (Anderson & Rivera Vargas, 2020).

From a social indicators' perspective, digital transformation provides capabilities to enhance mental health and emotional well-being, ensuring social inclusion, equity in access, community engagement, and pedagogical adaptability. Timmis (2012) earlier demonstrated that informal communication networks via messaging platforms strengthened peer support structures, creating sustainable academic ecosystems. Additionally, interactive strategies such as game-

based and problem-based learning, including the use of Augmented Reality (AR), contribute to increased student motivation, collaboration, and sustained academic engagement (Lee, 2022).

Nonetheless, despite the positive societal-related effect, digitally-driven transformations of educational environments (such as the forced migration to remote modalities) faces the systemic inequality challenge, in particular, for students with limited digital infrastructure, or inadequate remote learning environments. These disparities call for the development of inclusive digital strategies that prioritize universal accessibility, flexible pedagogical models, and well-being-oriented design. Hence, social sustainability in smart campuses emerges as a critical aspect: while digital transformation provides flexible learning, equitable access and digital inclusion remain pressing issues.

Therefore, the advancement of smart campuses through digital transformation necessitates the integration of social sustainability indicators into their foundational design. Key elements such as ethical data governance, mental health support, equitable access to digital infrastructure, and inclusive, participatory learning environments are critical to ensuring that technological innovation contributes meaningfully to SDGs, particularly SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), and SDG 10 (Reduced Inequalities).

4.3 – *Digital transformation and sustainability outcomes for smart campus: governmental indicators*

The studies in this category focus on the potential of digital technologies to reshape governance dynamics by advancing digitally empowered institutional sustainability within smart campus ecosystems. These technologies enhance digitally-empowered institutional sustainability providing digital capabilities to enable participatory, transparent, and responsive institutional practices (see Table 1). Therefore, the "governance transformation" dimensions addresses how smart technologies must be embedded in institutional policies to ensure long-term campus sustainability, improving governance coordination and fostering leadership engagement (Silva-da-Nóbrega *et al*., 2022). Governance models that integrate participatory approaches, like peer-to-peer digital training platforms, are increasingly recognized as essential to ensure transparency, inclusion, and accountability in smart campus development. One particular governance model which illustrates this shift towards co-governance paradigm is the Green Office Model. It utilizes digital technologies to enable students, staff, and faculty as proactive agents of change.

Such governance innovations demonstrate that participatory, ethics-driven management structures can empower community stakeholders and enhance institutional accountability (Adomßent *et al*., 2019). Through the integration of communication platforms, peer-to-peer digital learning programs, and decentralized networks, digital tools facilitate bottom-up governance, encouraging campus actors to self-organize, co-design, and lead the sustainability initiatives. Technologies, such as instant messaging apps and online collaboration systems, support democratic participation and build capacity for local governance, thereby fostering emotional resilience and enhancing the social dimension of sustainability.

However, the increased reliance on digital surveillance mechanisms, such as online exam proctoring, poses ethical governance challenges (Selwyn *et al*., 2023). These technologies risk eroding trust and infringing on privacy rights if not implemented within well-defined frameworks for digital ethics, accountability, and inclusiveness. Consequently, smart campus digitalization requires governance models that emphasize rights-based approaches, regulatory

oversight, and ethical data stewardship to ensure that efficiency gains do not come at the expense of human-centric values.

Hence, the development of digitally enabled smart campuses offers significant potential to enhance key governmental sustainability indicators, embedding participatory governance into institutional frameworks. This approach aligns with broader governmental indicators such as participatory governance, institutional transparency, public accountability, and digital inclusion, all of which are integral to achieving SDGs, particularly SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships for the Goals). A carefully managed digital transformation, grounded in ethical principles, is essential for reinforcing the role of higher education institutions as incubators of sustainable governance and innovation.

Therefore, the analysis reveals a growing interconnection between digitalization and sustainability, structured through the ESG framework. Environmental sustainability in smart campuses increasingly reflects not only operational efficiency but also proactive climate responsibility. Socially, digital transformation is reshaping student engagement and access; however, persistent challenges related to digital inequality and inclusive participation underscore the need for sustainable and accessible digital learning environments. In governance, digital tools offer new forms of academic oversight, yet also raise concerns about ethics, privacy, and data governance, requiring robust institutional frameworks. In such a way, the integration of technological infrastructures, stakeholder engagement, and transformative governance highlights that smart campus concept is no longer strictly related to the technological innovation adjustment, but at the same time, covers challenges to provide digitally-driven sustainability within educational ecosystems.

5 – Conclusion and future research agenda

The findings of this study, grounded in the bibliometric and content analysis of the most influential contributions to smart campus research, highlight the emergence of smart campuses as complex, digitally enabled ecosystems designed to promote sustainability across ESG dimensions. The intersection of digitalization and sustainability within higher education institutions is progressively maturing into a structured academic and operational paradigm, reflecting broader societal shifts towards technology-driven sustainable development. The ESG framework emerges as a comprehensive analytical lens for understanding how environmental management, social equity, and governance innovation intersect in the digital transformation of higher education. In such a way, the study provides an integrative analytical framework that situates smart campus development within the broader context of ESG-aligned digital transformation.

From a theoretical standpoint, the study suggests a conceptual framework that integrates previously fragmented research on sustainability and digitalization, thereby contributing to the evolving body of scholarship on digitainability in the context of higher education institutions. The analysis challenges linear and deterministic assumptions of digital progress by positioning digital tools not as inherent drivers of sustainability, but as strategic, mediating mechanisms whose impact depends on governance, implementation, and alignment with institutional values. The findings emphasize that the sustainability potential of digital transformation is contingent upon inclusive, participatory, and ethically grounded campus strategies. Thereby, the study reframes technological innovation as context-dependent and embedded within broader sustainability imperatives. Furthermore, the research provides insights for practitioners

(e.g. university administrators, campus planners, technology providers, and policymakers) in order to design inclusive, context-sensitive digital strategies that support long-term institutional sustainability. The ESG-framed approach introduced herein supports the development of integrated strategies that align technological infrastructures with sustainability objectives.

Acknowledging its limitations, the study draws exclusively on Scopus-indexed literature, which may narrow disciplinary diversity and overlook emergent interdisciplinary contributions indexed elsewhere. Future research should consider broader database integration and longitudinal analyses to capture evolving trends in digitainability, as well as region-specific investigations to reflect socio-political variability in the adoption of digital sustainability practices. Moreover, expanding the technological scope to include emerging tools such as AI, blockchain, digital twins, and ethics-by-design frameworks could provide a deeper understanding of how advanced systems contribute to, or complicate, sustainability outcomes.

In summary, this study contributes to bridging the conceptual and empirical fragmentation in the literature on digital transformation and sustainability in higher education. Providing linkage between ESG frameworks with the digitainability paradigm, it positions smart campus initiatives as key vectors for ethical, sustainable, and technologically grounded institutional innovation. Thereby, it strengthens the theoretical foundations of emerging e-campus research while offering actionable insights for shaping the next generation of sustainable digital universities.

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