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Bibliometric Insights into Computational Thinking and Green Computing Awareness: Emerging Trends Toward Sustainable Digital Pedagogy (2015–2024)

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ABSTRACT
The digital transformation in higher education requires the integration of computational literacy and environmental awareness to achieve sustainable learning practices. This study aims to map the interrelation between Computational Thinking (CT), Green Computing Awareness (GCA), and the use of statistical analysis software within the framework of Sustainable Digital Pedagogy. The research employed a descriptive bibliometric approach. The dataset consisted of 60 documents refined from the Scopus database covering the 2015–2024 period. Data were analyzed using the analyze results feature on the Scopus website and the VOSviewer software to identify publication trends, thematic networks, and the global evolution of related studies. The findings reveal that CT occupies the most central position in the research landscape, while GCA forms an independent cluster emphasizing energy efficiency and technological sustainability. The use of statistical analysis software serves as a conceptual bridge between the two domains. These findings highlight the need for an integrative approach that combines cognitive, ecological, and analytical dimensions in higher education. This study provides conceptual insights and strategic implications for developing curricula and green digital campus policies oriented toward sustainability.

INTRODUCTION

The evolution of digital technology has profoundly transformed how thinking, learning, and research are conducted in higher education. Yet, this transformation entails a paradox: the expansion of human computational capacity coincides with escalating digital energy consumption and an increasing global carbon footprint (Dura et al., 2022;Ewim et al., 2023). This situation calls for educational paradigms that transcend mere technological proficiency by embedding sustainability and ecological responsibility within academic practice (Al-Nuaimi & Al ‐ Ghamdi, 2022;Cardiff et al., 2024).

Within the higher education domain, Computational Thinking (CT) has been widely recognized as a cornerstone of twenty-first-century competencies, equipping learners with algorithmic reasoning, analytical insight, and data-driven problem-solving abilities (Babazadeh and Negrini 2022; I. F.

Christensen 2023; González-Pérez and Soledad 2022; Long et al. 2024; ŞENER and Umutlu 2024). In parallel, Green Computing Awareness (GCA) represents a vital framework for fostering responsible and energy-efficient digital behavior (Firmansyah, Sudirman, and Putra 2024; Omoyajowo et al. 2024; Tongal et al. 2024). Together, CT and GCA are pivotal in cultivating a generation of digitally competent scholars who are equally committed to ecological sustainability.

However, the integration of CT and GCA within higher education remains limited. Existing studies tend to examine these domains in isolation: CT research primarily addresses cognitive and programming aspects (Liu 2024; ŞENER and Umutlu 2024; Wei et al. 2024; Yurdakök and Kalelıoğlu 2023; Zakwandi and Istiyono 2023), whereas GCA studies emphasize energy efficiency within the information technology sector (Atadoga et al. 2024; Bichaiah 2022; Bose and Nag 2022; Kumar et al. 2023; Wang et al. 2023). In an era characterized by data-driven education, CT offers a foundational pathway to embed environmental awareness through sustainable data analysis, modeling, and visualization (Christensen, 2022).

An underexplored yet promising dimension lies in the pedagogical role of statistical analysis tools such as JASP in linking CT and GCA. Beyond facilitating data analytics, such software embodies green computing principles through open-source accessibility, computational efficiency, and reproducibility (Darwas et al. 2025; Niu et al. 2021; Prabawa, Rosjanuardi, and Nurlaelah 2024; Wang et al. 2023). Thus, modern statistical applications can serve as educational mediators that bridge computational proficiency and sustainability consciousness.

While earlier studies (Akcaoglu, Özcan, and Hodges 2023; Aristizábal Zapata, Gutiérrez Posada, and Diago 2024; D. Christensen 2022; Ibrohim, Siregar, and Chaeruman 2023; Kanaki and Kalogiannakis 2023; Niu et al. 2021; Peters et al. 2024; Prabawa, Rosjanuardi, and Nurlaelah 2024; Prabawa[1], Rosjanuardi, and Nurlaelah 2024) have touched upon aspects of this intersection, a comprehensive bibliometric synthesis remains absent. Specifically, there is a lack of systematic mapping illustrating how CT, GCA, and statistical software converge, evolve, and interact within the academic context. Addressing this gap, the present study proposes an integrative framework Sustainable Digital Pedagogy that unites the cognitive (CT), ethical-ecological (GCA), and analytical-technological (statistical software) dimensions. Through bibliometric analysis of international publications from 2015 to 2024, this study seeks to outline the intellectual landscape and emerging research frontiers, offering a strategic roadmap for scholars and educators committed to fostering data-driven, technologically adaptive, and environmentally responsible higher education.

METHODS

This research adopts a quantitative approach employing a descriptive–analytical bibliometric method to map, analyze, and visualize the evolution and intellectual structure of studies exploring the interplay between Computational Thinking (CT), Green Computing Awareness (GCA), and the utilization of statistical analysis software in higher education contexts. Data were systematically retrieved from the Scopus database using the query string (TITLE-ABS-KEY(green computing) AND TITLE-ABS-KEY(green ict) AND TITLE-ABS-KEY(sustainable computing) OR TITLE-ABS-KEY(computational thinking) OR TITLE-ABS-KEY(statistics education)) AND (LIMIT-TO (OA,"all")) AND PUBYEAR > 2015 AND PUBYEAR < 2024). The search was restricted to English-language articles and conference papers published between 2015 and 2024. Following the initial search, records were screened based on relevance to higher education, resulting in a final dataset of 60 documents meeting the inclusion criteria for bibliometric analysis.

To ensure data reliability and relevance, the dataset underwent a rigorous data-cleaning process. The bibliometric workflow consisted of five analytical stages: (1) defining search keywords, (2) obtaining initial results, (3) refining search outcomes, (4) compiling preliminary statistical summaries, and (5) conducting in-depth data analysis (Ajito et al. 2025; Meiyenti et al. 2024; Riyanto et al. 2024; Suprapto et al. 2024). All analyses and visualizations were performed using the Analyze Results tool

on Scopus and the Bibliometrix VOSviewer software, enabling a comprehensive exploration of conceptual linkages among CT, GCA, and the adoption of statistical software as foundational elements for fostering digital sustainability–driven pedagogical innovation in higher education.

RESULTS AND DISCUSSION

The bibliometric analysis encompassed 60 curated documents that were selected following a rigorous screening of the initial search results retrieved from the Scopus database. The analytical process comprised two major phases. In the first phase, quantitative indicators including publication trends by year, subject area, and country were extracted directly from the Analyze Results feature on the Scopus platform to depict the overall distribution and temporal dynamics of scholarly output. In the second phase, the complete bibliographic dataset was processed using VOSviewer software to construct network, overlay, and density visualizations, enabling the identification of conceptual relationships and thematic concentrations within the research landscape.

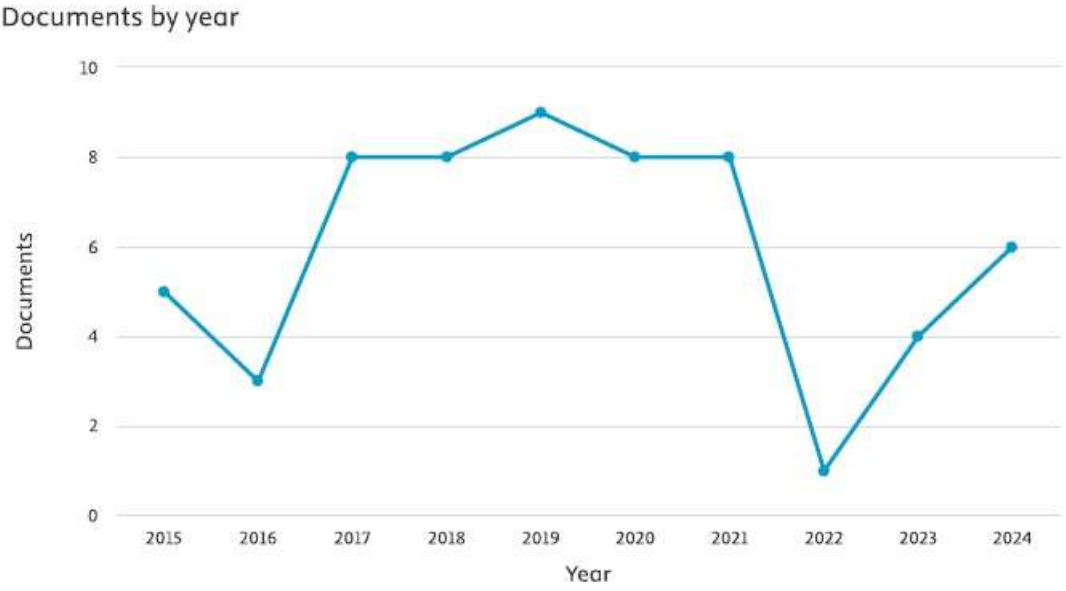
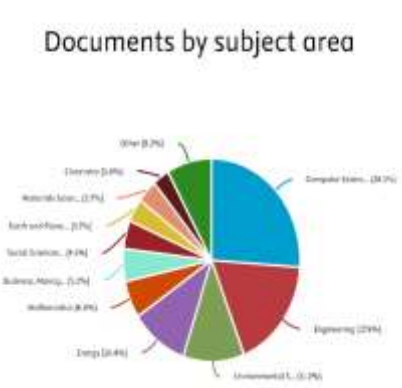


Figure 1. Documents by Years

As illustrated in Figure 1, the bibliometric exploration of the Scopus database from 2015 to 2024 reveals a fluctuating trajectory in the volume of publications addressing Computational Thinking (CT), Green Computing Awareness (GCA), and the application of statistical analysis software within higher education contexts. Publication output exhibited a marked increase between 2016 and 2019, reaching its peak in 2019, followed by a period of relative stability through 2020. After a sharp decline in 2022, the trend rebounded in 2023–2024, suggesting renewed scholarly attention to these interrelated domains. This temporal pattern reflects a dynamic research landscape shaped by global shifts in digital education policies and the rising academic interest in sustainable digital pedagogy. The upward trajectory of publication activity can be further analyzed through the disciplinary and geographical distributions of research outputs, as depicted in Figures 2 and 3.



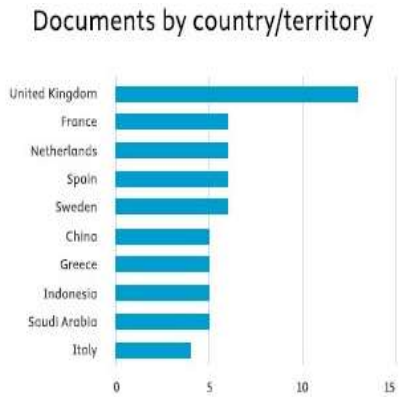


Figure 2. Documents by Subject Area Figure 3. Documents by country/territory

As illustrated in Figures 2 and 3, the majority of publications are concentrated within the domains of computer science, engineering, and environmental studies. A notable proportion of contributions originates from countries such as the United Kingdom, France, the Netherlands, and Indonesia, reflecting the global and collaborative nature of the research landscape. This distribution pattern underscores that computational literacy and eco-technological awareness have emerged as increasingly strategic and interdisciplinary focal points across geographical boundaries in the context of 21st-century education. Following the identification of disciplinary and geographical distributions, the analysis proceeded with keyword co-occurrence mapping to uncover the underlying thematic structures of global research within this field.

Figure 4. Network Visualization

As depicted in Figure 4, the network visualization reveals that CT occupies a central position within the keyword co-occurrence map, highlighting its role as a core conceptual theme in higher education curriculum development. Meanwhile, GCA forms an independent cluster closely associated with topics such as sustainable ICT and green machine, reflecting a growing research emphasis on environmental consciousness and digital energy efficiency. The use of statistical analysis software emerges as a supporting node connecting these two domains, underscoring the strategic integration of

computational literacy, eco-technological awareness, and sustainable digital practices as key directions in contemporary higher education research.

Nevertheless, the network visualization indicates that there are still limited significant linkages among the nodes, suggesting that CT, GCA, and the use of statistical analysis software remain relatively distinct research domains. The absence of strong interconnections implies that thematic collaboration among these keywords has yet to be fully consolidated in the current body of literature(Fadiji et al. 2023; Jiang et al. 2023; Yang et al. 2025; Zhong et al. 2022). However, the close proximity between nodes—particularly among CT, sustainable software, and educational curricula suggests potential conceptual relationships that could be further developed through interdisciplinary research approaches within the framework of sustainable eco-technological higher education (Ahlgren et al. 2023; Duan et al. 2023). To further capture the temporal dynamics among these research topics, overlay visualization analysis was employed to illustrate the evolution of thematic focus over time.

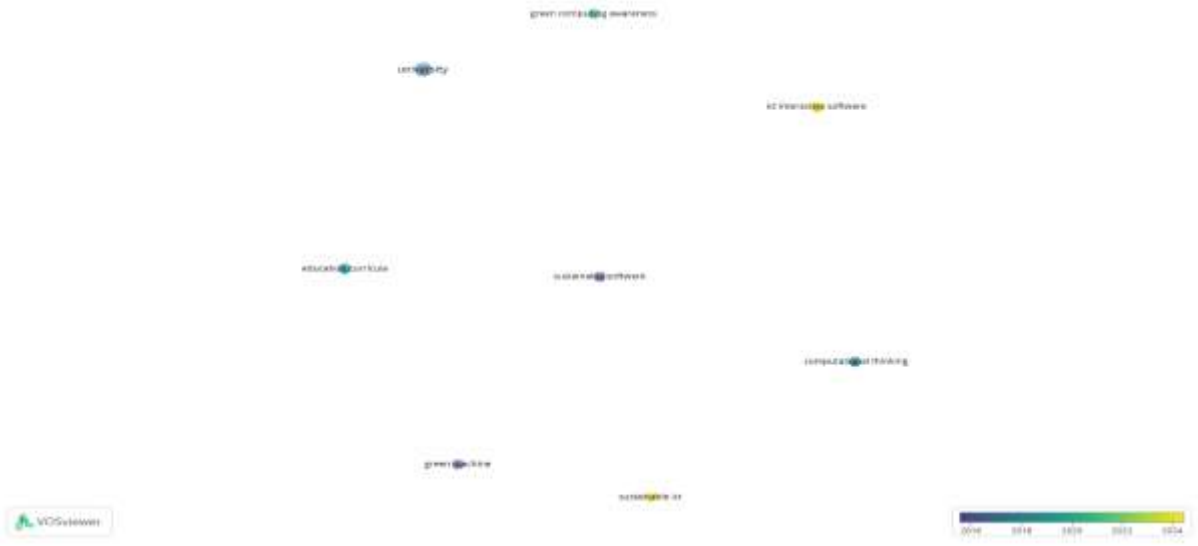


Figure 5. Overlay Visualization

The overlay visualization employs a color gradient to represent the temporal emergence of research topics, where light blue to green indicates earlier topics, while yellow denotes more recent term (Judijanto 2025; Zaharuddin et al. 2024;Ria and Susilowati 2023). As illustrated in Figure 5, topics such as Computational Thinking (CT) and sustainable ICT emerged earlier, around 2016–2018 (represented by light blue to green tones). In contrast, terms such as green computing awareness, ICT interactive software, and sustainable software appeared later, during the 2020–2024 period (yellow tones), reflecting a shift in research focus toward digital sustainability and eco-technological awareness (Song et al. 2022).

The absence of connecting lines among nodes indicates that thematic interrelations between these topics remain weak, even though the close spatial proximity of CT, sustainable software, and educational curricula nodes suggests potential conceptual integration in future research (Nugraheny et al. 2024). These findings affirm that research on computational literacy and green computing within higher education continues to evolve toward a more interdisciplinary and sustainability-oriented

direction. Subsequently, to examine the intensity and concentration of major themes, a density visualization analysis was conducted (Kartakusumah et al. 2023).

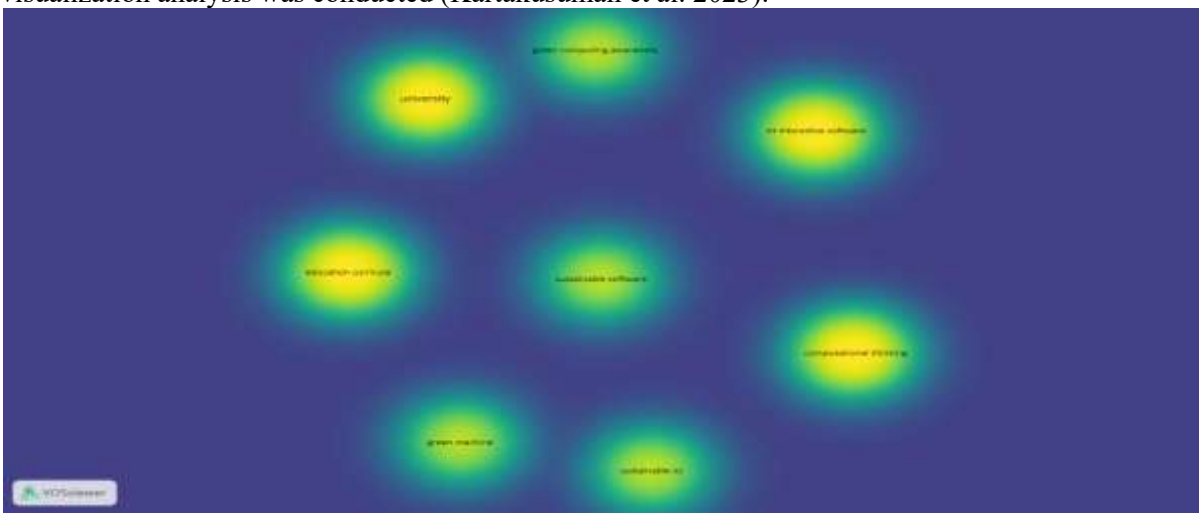


Figure 6. Density Visualization

As illustrated in Figure 6, the density visualization highlights yellow-colored regions representing keywords with the highest frequency and concentration (Gong et al. 2024; Kurniawati et al. 2025;Susilowati et al. 2024), notably CT, educational curricula, and sustainable software. These terms constitute the core thematic focus within the discourse on computational literacy and digital sustainability. In contrast, keywords such as GCA, ICT interactive software, and green machine—represented in green areas with medium density(Ju 2024; Ridwana et al. 2024), reflect emerging research domains with considerable potential for integration into sustainable education frameworks. The relatively even distribution of clusters, with minimal overlap, suggests that scholarship in this area remains at an exploratory stage, offering substantial opportunities for strengthening thematic connectivity in future studies. Collectively, these patterns reaffirm the convergence of CT, GCA, and software analytics toward the Sustainable Digital Pedagogy paradigm, emphasizing the advancement of sustainable digital literacy.

A notable research gap also emerges from this visualization. While previous studies (Akcaoglu, Özcan, and Hodges 2023; Aristizábal Zapata, Gutiérrez Posada, and Diago 2024; D. Christensen 2022; Ibrohim, Siregar, and Chaeruman 2023; Kanaki and Kalogiannakis 2023; Niu et al. 2021; Peters et al. 2024; Prabawa, Rosjanuardi, and Nurlaelah 2024; Prabawa[1], Rosjanuardi, and Nurlaelah 2024) have explored partial intersections among these domains, no comprehensive bibliometric synthesis has yet examined how CT, GCA, and statistical software usage co-evolve and interact within higher education research. This gap underscores the necessity for an integrative framework capturing the evolution, convergence, and prospective trajectories of these intertwined scholarly areas.

The novelty of the present study lies in its integrative perspective, uniting three critical dimensions: the cognitive dimension represented by CT, the ethical–ecological dimension embodied by GCA, and the technological–analytical dimension reflected in the use of statistical software. Together, these elements form the conceptual foundation of Sustainable Digital Pedagogy a framework that advances not only digital literacy but also ecological responsibility and resource efficiency. This approach offers a transformative lens for interpreting the digital transformation of higher education, moving beyond a purely technological orientation toward sustainability and ethical stewardship.

In broader terms, the findings have strategic implications for curriculum innovation and policy formulation in higher education. Integrating CT, GCA, and software analytics can foster data-driven, environmentally responsible learning ecosystems aligned with 21st-century competencies. Universities

can utilize these insights to design interdisciplinary curricula, promote transnational research collaborations, and strengthen institutional governance guided by the principles of digital sustainability. Thus, this bibliometric mapping not only delineates the global research landscape but also provides a strategic blueprint for cultivating higher education systems that are intelligent, green, and responsive to technological evolution.

CONCLUSIONS

This study reveals that CT occupies a pivotal position within the higher education research landscape, whereas GCA has emerged as an evolving thematic field emphasizing environmental consciousness in digital technology practices. The application of statistical analysis software functions as a conceptual bridge linking these two domains, illustrating a growing research trajectory toward the integration of computational literacy, eco-technological awareness, and digital analytical capability. The study's novelty resides in its integrative framework of Sustainable Digital Pedagogy, which cohesively unites cognitive, ecological, and analytical dimensions. This framework not only advances theoretical understanding but also offers a robust conceptual basis for fostering higher education that is data-informed, technologically progressive, and sustainability-oriented.

From a practical standpoint, the findings provide valuable insights for educators and policymakers to design curricula that incorporate green digital literacy and energy-efficient learning practices. However, the study acknowledges certain limitations, particularly the exclusive use of bibliometric data from a single indexing source (Scopus) and the primarily descriptive nature of the analysis, which may restrict the generalizability of the results. Future research is therefore encouraged to adopt multi-database analyses and employ mixed bibliometric–qualitative approaches to deepen insights into this emerging interdisciplinary nexus.

RECOMMENDATIONS

Future studies are encouraged to complement bibliometric methods with empirical analyses in order to quantitatively validate the interrelationships among key variables. Moreover, the inclusion of multiple databases, such as Web of Science and Dimensions would enhance the comprehensiveness of data coverage and provide a more nuanced understanding of global research dynamics. Cross-national comparative investigations are likewise essential to assess how the integration of CT, GCA, and statistical analysis tools is contextualized and operationalized within diverse higher education systems.

LIMITATIONS

This study acknowledges several limitations. First, the data were drawn solely from the Scopus database, which may exclude relevant publications indexed elsewhere. Second, the bibliometric approach employed is descriptive in nature and therefore does not capture causal relationships or empirical interactions among variables such as CT, GCA, and the use of statistical analysis software. Third, the analytical period of 2015–2024 may not fully represent long-term trends or post-2024 developments.

Nevertheless, these limitations open opportunities for future studies to expand data sources by integrating additional databases such as Web of Science and Dimensions, combine bibliometric techniques with quantitative and qualitative analyses, and conduct longitudinal investigations. Such efforts would contribute to a more comprehensive understanding of the roles of computational literacy, eco-technological awareness, and data analytics in advancing sustainable higher education transformation.

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