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Mapping Computational Thinking in the Era of Digital Transformation for Education toward SDG 4: A Bibliometric Analysis

Afra Lathifah[1], Adrie Satrio[2], Liana Mumrikoh[3]
[1,2] Teacher Professional Education, Universitas Bengkulu, Bengkulu, Indonesia
[3] Information Technology Education, Universitas Nurul Huda, Ogan Komering Ulu Timur, Indonesia
E-mail: [1]afra.lathifah@unib.ac.id*, [2]adrie.satrio@unib.ac.id , [3]lianamumrikoh@unuha.ac.id
*Coresponding Author

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ABSTRACT

Computational Thinking (CT) has emerged as an important competency in education in response to ongoing digital transformation and the increasing emphasis on Sustainable Development Goal 4 (SDG 4). This study employs bibliometric analysis to examine CT-related publications from 2015 to 2025. Network, cluster, and overlay visualization techniques were used to identify key research trends, thematic developments, and collaboration patterns in the field. The results indicate a continuous growth in CT research and a shift from viewing CT primarily as a programming skill toward a broader cognitive and pedagogical construct involving problem solving, abstraction, and adaptive reasoning. CT is predominantly associated with workforce preparation, teacher capacity-building, and instructional innovation across educational contexts. While research has expanded into areas such as early childhood education and digital learning environments, topics related to equity, sustainability, and global citizenship remain relatively underexplored. Overall, this study highlights the evolving conceptualization of CT in education and underscores the need for more inclusive and sustainability-oriented research in future studies.

Keywords: *Computational Thinking, Digital Transformation, Bibliometric Analysis, SDG 4, Education*

INTRODUCTION

Digital transformation has significantly changed educational, social, and professional practices in contemporary society. The rapid growth of technologies such as artificial intelligence, big data, and the Internet of Things has increased the demand for individuals who possess digital literacy and strong problem-solving skills. In addition, emerging educational technologies such as the metaverse are reshaping learning environments by enabling more immersive, interactive, and virtual-based educational experiences (Alhakimi, 2023). As a result, education systems are expected to prepare students with skills relevant to the modern workforce and the Sustainable Development Goals (SDGs). Among these competencies, Computational Thinking (CT) has emerged as an important problem-solving framework, encompassing decomposition, abstraction, pattern recognition, algorithmic design, and evaluation (Shute et al., 2017; Voogt et al., 2015). Consequently, CT has gained increasing attention in discussions of digital transformation and education.

Although CT originated in computer science, it is now applied in various disciplines, including mathematics, science, and engineering education. Several studies have shown that CT can be integrated into mathematics, science, engineering, social studies, and interdisciplinary learning environments to enhance analytical reasoning and creativity (Li et al., 2020; Weintrop et al., 2016). Within mathematics and science education, CT supports modelling, simulation, data interpretation, and logical reasoning. In broader educational contexts, CT also supports collaboration, creativity, and adaptive thinking skills. These characteristics make CT relevant to the achievement of SDG 4, which aims to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

Recent studies have reported several educational benefits associated with CT. For example, a systematic review by Tang et al. (2020) found that CT interventions positively influence students' problem-solving skills, programming comprehension, and cognitive performance. Lee et al. (2022) similarly reported that CT-based learning raises engagement, creativity, and academic achievement in K–12 contexts. In STEM education, CT is associated with greater innovation capacity and improved practical problem-solving (Tariq et al., 2025). Supporting this, computational thinking is also closely linked to metacognitive processes that enhance learners' self-regulation and cognitive control (Buwono et al., 2025). These findings suggest that CT can contribute to improving educational quality and helping students adapt to technology-driven environments.

Despite these benefits, CT implementation still varies considerably across countries and educational systems. While many developed countries have integrated CT into school curricula, teacher training, and national digital strategies, developing countries continue to face challenges in infrastructure, curriculum development, teacher expertise, and policy integration. Furthermore, CT is frequently interpreted narrowly as coding or programming, thereby limiting its broader pedagogical potential as a cross-disciplinary cognitive approach (Grover & Pea, 2018). Differences in how CT is defined, assessed, and taught also create challenges for curriculum integration. These disparities may limit the role of CT in supporting equitable digital transformation.

The growing number of CT studies has increased the need for bibliometric analyses that map research trends and developments in the field. Bibliometric studies have begun to examine publication trends, influential authors, collaboration networks, and emerging research themes. Rafiq et al. (2023) observed a substantial increase in CT research output from 1987 to 2023, particularly after 2015, with major contributions from technologically advanced countries. Recent research has studied domain-specific topics such as science learning for SDGs (Erwinsyah et al., 2025), CT and project-based learning for SDG 6 (Samodra et al., 2025), CT in mathematics education (Sumarno et al., 2025), and CT in children's education for sustainable futures (Mee et al., 2025).

However, despite this growing body of literature, three main limitations can still be observed in many studies published between 2020 and 2025. First, the research is often spread across different areas (such as STEM education, programming, and specific SDG topics), rather than providing an integrated perspective. Second, many studies primarily rely on basic bibliometric measures such as publication counts, citation analysis, and author productivity. Third, the relationship between computational thinking, digital transformation, and SDG 4 has not yet been consistently examined within a unified bibliometric framework, as these topics are frequently treated separately at either thematic or descriptive levels.

Accordingly, this study presents a bibliometric analysis of CT research in the context of digital transformation and SDG 4. This study examines publication trends, influential authors, country contributions, and keyword co-occurrence patterns to understand how CT research has developed globally. It applies a combined approach that includes performance analysis, science mapping, and thematic visualization within a single framework. This approach provides a more complete overview of the main structure and themes in CT research by positioning computational thinking within both digital transformation and SDG 4 discussions, rather than treating them separately. In this way, the study offers a more connected view of the field and helps explain the development of CT research in education over time. Ultimately, this study aims to show how CT contributes to improving educational quality, equity, and sustainability in the era of digital transformation.

METHODS

This study employed a bibliometric approach to examine research on computational thinking in the context of digital transformation and its relation to SDG 4 on quality education. Bibliometric analysis is commonly used to identify publication trends, research patterns, and the development of scientific fields (Donthu et al., 2021). Data were collected using Publish or Perish (PoP) software with Google Scholar as the primary database. Google Scholar was selected because it provides broad coverage of international publications, including journal articles, conference papers, and early-access studies (Halevi et al., 2017). The search focused on publications published between 2015 and 2025 to capture recent developments in digital transformation and education.

The research procedure was conducted chronologically in four stages: data searching, data screening, data extraction, and bibliometric analysis. In the first stage, combinations of keywords related to computational thinking (e.g., “computational thinking”, “algorithmic thinking”), digital transformation (e.g., “digital learning”, “digital skills”, “educational technology”), and SDG 4 (e.g., “quality education”, “sustainable development goals”) were used. The keywords were combined using the Boolean operators “AND” and “OR” to ensure comprehensive retrieval of relevant publications. To obtain a broad yet manageable dataset, the 200 most relevant publications from each keyword group were selected, resulting in an initial dataset of 600 documents. Only publications written in English were included in the analysis.

In the second stage, the collected documents underwent several filtering processes to improve dataset relevance and consistency. After duplicate removal, 573 documents remained. The titles and abstracts were manually screened to identify studies specifically related to computational thinking and SDG 4, resulting in 152 relevant documents. In the final screening stage, books and reports were excluded to maintain consistency in publication type and focus only on peer-reviewed journal articles and conference papers. The final dataset consisted of 148 publications.

In the third stage, all selected documents were exported in RIS format for data extraction using VOSviewer software. Bibliographic information such as titles, authors, keywords, publication years, and citation data was organized and prepared for visualization analysis.

In the fourth stage, bibliometric analysis was conducted using VOSviewer. The analysis consisted of three visualization methods. First, network visualization was applied to identify relationships among keywords, authors, and publications. Second, overlay visualization was used to examine the evolution of research topics over time based on the average publication year. Third, density visualization was conducted to identify the most frequently discussed topics within the dataset (Cobo et al., 2011; van Eck & Waltman, 2010).

RESULTS AND DISCUSSION

Results

1. *Most Influential Publications in Computational Thinking Research*

Bibliometric analysis identified the 10 most influential publications on CT during the period of digital transformation (see **Table 1).** Korkmaz et al. (2017) received the highest number of citations (928), mainly due to the development of a widely used instrument for measuring CT skills. Nouri et al. (2020) focused on integrating programming and digital competencies in K–9 education, while Oliveira and De Souza (2022) recorded the highest average citation rate per year (110.25 citations), reflecting growing interest in Education 4.0. Other highly cited studies examined CT integration in STEM education (Wang et al., 2022), mathematics learning (Sung et al., 2017), game-based learning (Hooshyar et al., 2021), Scratch-supported distance learning (Marcelino et al., 2018), CT assessment approaches (Cutumisu et al., 2019), and robot programming in early childhood education (Yang et al., 2022).

Table 1. List of Influential Articles

Cites	Authors	Title	Cites Per Year	Country
928	Korkmaz et al. (2017)	A validity and reliability study of the computational thinking scales (CTS)	103.11	Turkey
513	Nouri et al. (2020)	Development of computational thinking, digital competence and 21st century skills when learning programming in K-9	85.50	Sweden
441	Oliveira and De Souza (2022)	Digital transformation towards education 4.0	110.25	Brazil
291	Wang et al. (2022)	Integrating computational thinking in STEM education: A literature review	72.75	USA
260	Sung et al. (2017)	Introducing computational thinking to young learners: Practicing computational perspectives through embodiment in mathematics education	28.89	USA
260	Iversen et al. (2018)	From computational thinking to computational empowerment: a 21st century PD agenda	32.50	Denmark
205	Marcelino et al. (2018)	Learning computational thinking and scratch at distance	25.63	Portugal
202	Hooshyar et al. (2021)	From gaming to computational thinking: An adaptive educational computer game-based learning approach	40.40	Estonia
192	Cutumisu et al. (2019)	A scoping review of empirical research on recent computational thinking assessments	27.43	Canada
159	Yang et al. (2022)	Robot programming versus block play in early childhood education: Effects on computational thinking, sequencing ability, and self-regulation	39.75	China

Overall, these influential studies demonstrate that CT has expanded across multiple educational contexts and technological approaches. Most highly cited publications were produced in Europe and North America, suggesting strong research activity in digital education within these regions.

2. *Thematic Clustering of Computational Thinking Research*

Co-occurrence analysis of terms in titles and abstracts revealed the thematic structure of CT literature within the context of digital transformation and SDG 4. The resulting clusters display the field's connections across policy, pedagogy, technology, and digital society (see **Figure 1**).

a. Cluster 1 is related to SDG 4, educational policy, teacher roles, and digital competence, highlighting the importance of 21st-century skills in quality education.
b. Cluster 2 focuses on classroom implementation of CT through project-based learning, creativity, Scratch programming, and robotics activities.
c. Cluster 3 represents the central area of CT research, including programming, teaching, digital learning environments, and higher education.
d. Cluster 4 is associated with digital transformation in education and broader social contexts.
e. Cluster 5 links CT with mathematics education, STEM learning, and digital learning tools.
f. Cluster 6 emphasizes foundational digital competence and basic digital skills that support CT development.
g. Cluster 7 reflects the interdisciplinary relationship between CT, science, and technology education.
h. Cluster 8 includes newer topics related to artificial intelligence and technology education.

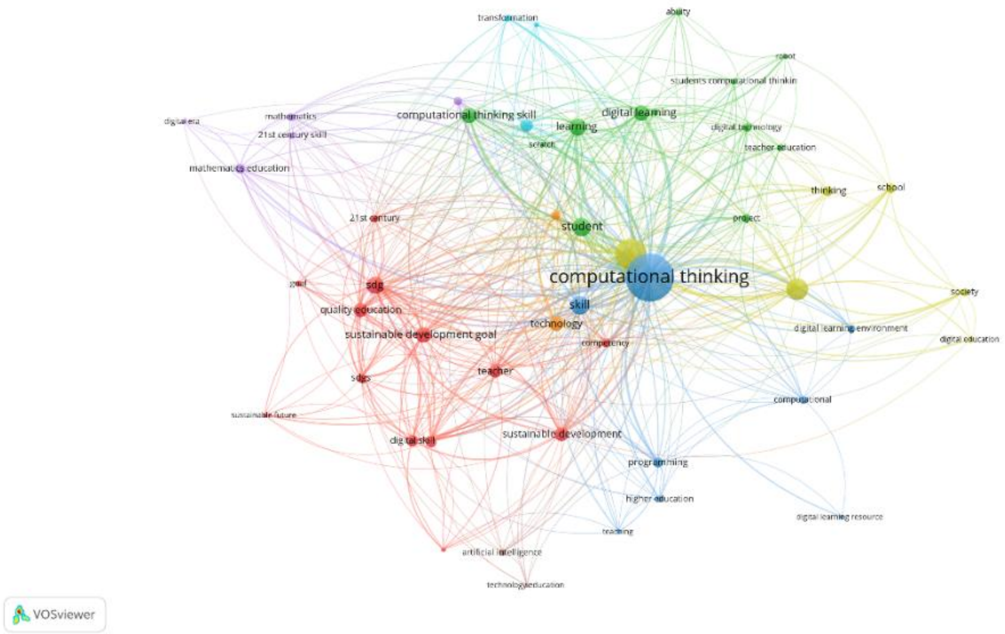

Figure 1. Network Visualization

3. Trends and Emerging Topics in Computational Thinking Publications

Publications on computational thinking increased steadily between 2015 and 2025, with a total of 148 publications identified in the dataset (see **Figure 2**). Publication growth became more noticeable after 2020, indicating increasing academic interest in CT within digital education contexts.

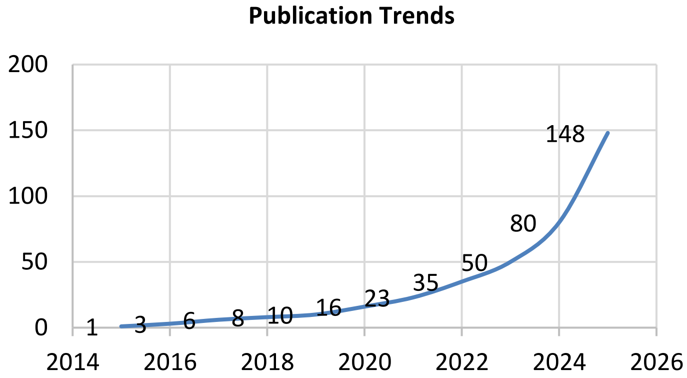

Figure 2. Number of Publications for The Period 2015-2025

Overlay visualization showed that many research topics were concentrated in the green area, suggesting that several themes have become relatively established in the literature (see **Figure 3**). At the same time, newer topics appearing in yellow emerged more frequently during the 2022–2025 period. These topics include digital transformation, SDG 4, and sustainability-oriented education. This pattern suggests that recent CT research has gradually expanded beyond programming and technical skills toward broader educational and societal issues.

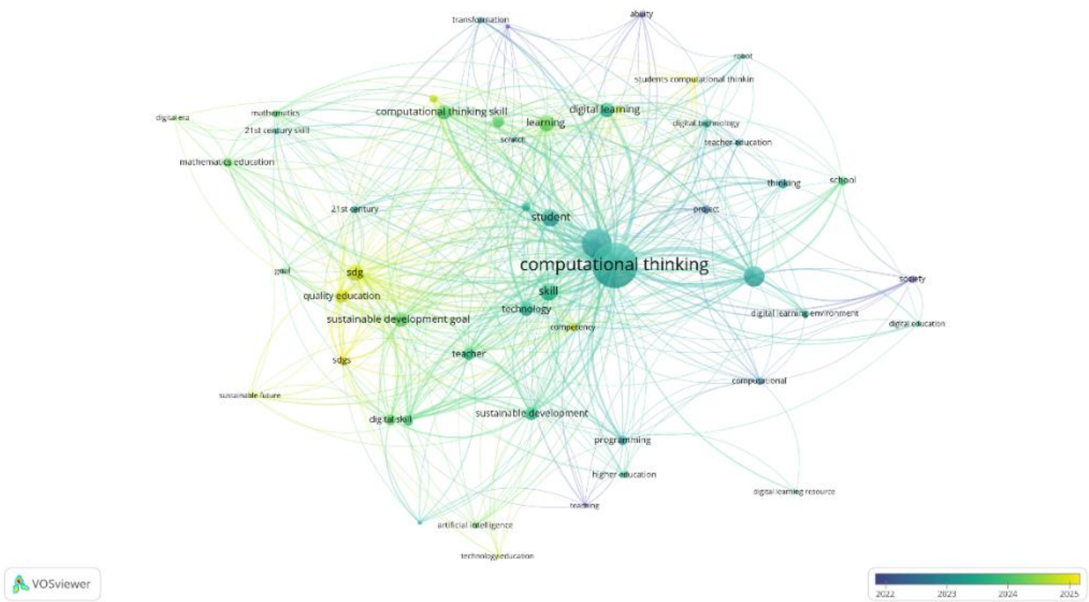

Figure 3. Overlay Visualization

4. Density Visualization of Research Topics

Density visualization highlighted several frequently occurring topics in the dataset, particularly *computational thinking*, *education*, *students, skills, technology,* and *digital transformation* (see **Figure 4**)**.** These terms reflect the dominant areas of focus within the current CT literature.

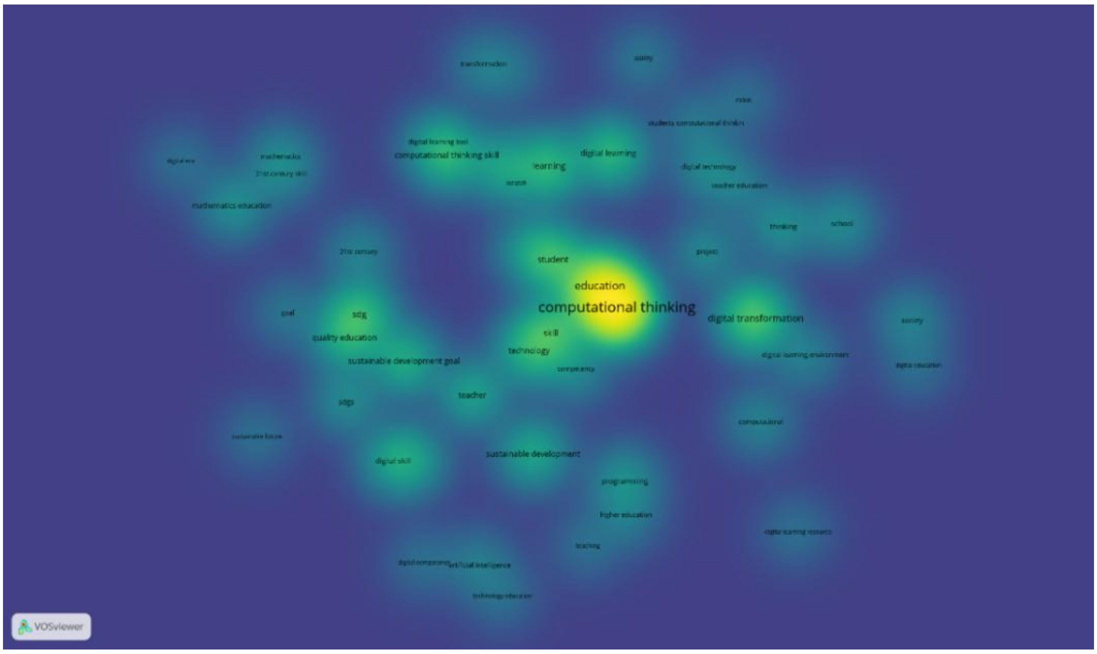

Figure 4. Density Visualization

Some related topics appeared with lower density levels. This does not necessarily indicate limited research activity, but rather differences in terminology used across studies. For example, similar concepts were described using terms such as digital learning resources, educational technology, digital technology, and digital learning environments. As a result, related keywords were distributed across different parts of the network.

Overall, the findings indicate that core CT themes are already well established, although terminology across studies remains relatively inconsistent.

Discussion

The results of this study show a clear increase in computational thinking (CT) research between 2015 and 2025, particularly in education-related contexts influenced by digital transformation. Over time, CT has clearly shifted from being discussed mainly as a programming or coding skill to a broader set of ideas involving problem-solving, abstraction, pattern recognition, and adaptive reasoning in a digital learning environment (Li et al., 2020; Wang et al., 2022). The overlay analysis shows that the field is now relatively mature, although new topics such as sustainability, artificial intelligence in education, and SDG-related learning are becoming more visible. Compared with recent bibliometric studies, Chen et al. (2023) and Rafiq et al. (2023), which similarly report the expansion of CT into interdisciplinary and technology-enhanced learning, this study extends the literature by positioning computational thinking research within the framework of SDG 4 targets, enabling a more structured understanding of how CT contributes to different dimensions of quality education.

In relation to SDG 4, CT is most strongly linked with Targets 4.4 and 4.c, particularly in skills development for employment and entrepreneurship and teacher capacity-building. Keyword co-occurrence (skills, learners, technology, digital transformation) shows a strong link between CT and workforce-oriented education. This aligns with Nouri et al. (2020) and Oliveira and De Souza (2022), as well as STEM-related studies (Tariq et al., 2025), but extends them by showing that digital transformation is not only a context, but a main factor that influences how CT research develops, especially within Education 4.0 and future skills development.

Teacher capacity-building (Target 4.c) remains essential for CT implementation. In line with Butler and Leahy (2021) and Liu et al. (2024), pedagogical competence and institutional support are more influential than technology access alone. However, unlike Ung et al. (2022), which emphasizes individual teacher capacity, this study highlights a shift toward broader digital learning systems within schools and institutions, suggesting a more sustainable implementation model. Nevertheless, most highly cited studies originate from Europe and North America, while evidence from developing countries remains relatively limited.

In formal education contexts (Targets 4.1 and 4.3), CT is increasingly applied through project-based learning, inquiry-based learning (Ogegbo & Ramnarain, 2022), Scratch (Marcelino et al., 2018), and robotics (Kerimbayev et al., 2023; Yang et al., 2022). Compared with earlier studies (Hooshyar et al., 2021; Sung et al., 2017), which focus mainly on engagement and cognition, this study shows that CT has expanded beyond STEM into disciplines such as business, health, and social sciences (Lee & Malyn-Smith, 2020), confirming its role as a skill that can be used across many subjects, not only STEM areas.

Moderate contributions are found in Targets 4.6, 4.2, and 4.a, particularly in literacy and numeracy development, early childhood education, and inclusive and effective learning environments. CT is strongly associated with logical thinking, sequencing, and data literacy, consistent with Korkmaz et al. (2017) and Bilbao et al. (2025), which provide structured ways to measure CT skills in different educational settings. In early childhood education, block-based programming and robotics improve early CT skills (Yang et al., 2022; Zeng et al., 2023). These findings indicate that CT develops in a stepwise manner across educational levels, depending on teaching methods and available facilities.

However, Targets 4.5, 4.7, and 4.b remain underexplored, particularly in relation to equitable and inclusive access to education, education for sustainable development and global citizenship, and scholarship opportunities for learners from developing countries. This aligns with Tikva and Tambouris (2021), who also report dominance of technical and employability perspectives. Nevertheless, emerging studies by Iversen et al. (2018) and Tongal et al. (2024) show a gradual shift toward computational empowerment, creativity, and sustainability-oriented learning, although these perspectives remain emerging rather than dominant.

Overall, CT research is associated with multiple SDG 4 targets, with the most frequent associations observed in skills development for employment and entrepreneurship (Target 4.4), teacher capacity-building (Target 4.c), and support for quality education at primary, secondary, and tertiary levels (Targets 4.1 and 4.3). Contributions to Targets 4.6, 4.2, and 4.a are also present, while Targets 4.5, 4.7, and 4.b are less frequently represented in the literature. These patterns indicate an uneven distribution of research attention across SDG 4 targets in CT studies within the context of digital transformation, with a stronger emphasis on employability-oriented skills and teacher development compared to educational inclusion, education for sustainable development, global citizenship, and human rights. By mapping CT research across SDG 4 targets, this study provides a structured overview of the distribution of scholarly attention across dimensions of educational development and identifies areas that may benefit from further research.

CONCLUSION

This study finds that CT has become a well-established research domain contributing to SDG 4 within the context of digital transformation. The results reveal a distinct shift in CT conceptualization from a focus on programming skills to broader competencies, including problem-solving, abstraction, pattern recognition, and adaptability. CT's strongest contributions are observed in Targets 4.4, 4.c, 4.1, and 4.3, particularly in skills development for employment and entrepreneurship, teacher capacity-building, and support for quality primary, secondary, and tertiary education. Moderate contributions are evident in Targets 4.6, 4.2, and 4.a, whereas

Targets 4.5, 4.7, and 4.b remain insufficiently addressed, particularly in relation to equitable and inclusive access to education, education for sustainable development and global citizenship, and scholarship opportunities for learners from developing countries. Overall, CT serves as both a technical and educational literacy, bridging digital transformation with broader educational objectives. The study highlights the uneven distribution of research attention across SDG 4 dimensions and calls for more integrated approaches that strengthen inclusion, sustainability, and educational equity in future CT research.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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