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Review

Design thinking in science and integrated STEM/STEAM education: Trends, challenges, and future directions from a systematic review

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Abstract: This study presents a dual-method systematic review synthesizing global research on implementing design thinking (DT) in science and integrated STEM/STEAM education between 2011 and 2024. Combining bibliometric analysis of 113 Scopus-indexed publications with a systematic literature review (SLR) of 40 empirical studies, this study examines trends, instructional contexts, theoretical frameworks, competencies, challenges, and future directions in DT pedagogy. The bibliometric results revealed a sharp rise in publications post-2018, with the United States, China, and Australia emerging as leading contributors. Citation analyses highlighted key authors, journals, and collaboration patterns, confirming DT's growing scholarly legitimacy and pedagogical relevance. The SLR findings demonstrated that DT is most commonly implemented using adapted versions of the Stanford d.school model, operationalized through empathy-driven tools, inquiry-based tasks, and iterative prototyping. While DT fosters a broad range of cognitive, creative, and socio-emotional competencies, its implementation is often hindered by teacher readiness, curriculum rigidity, and insufficient assessment mechanisms. To address these gaps, the study proposes the ECLIPSE-DT Framework, a theoretically grounded, empirically informed model comprising seven interconnected components: empathic engagement, contextual integration, learner agency, inquiry orientation, process scaffolding, scalability planning, and evaluation mechanisms. This framework provides a pragmatic and research-based structure to guide the effective integration of DT into science education, aligning creativity, empathy, and sustainability with curricular demands. The study outlines future research and policy recommendations, emphasizing the need for more profound theoretical articulation, interdisciplinary integration, and scalable implementation of DT-based pedagogies across educational levels.

Keywords: design thinking, science education, STEM/STEAM, ECLIPSE-DT framework, bibliometric analysis, systematic literature review, empathy, sustainability, 21st-century skills

1. Introduction

Design thinking (DT) has emerged as a significant pedagogical approach in recent decades, increasingly influencing various domains, including education, business, engineering, and public policy [1,2]. Initially conceptualized by Simon [3] as a three-phase problem-solving method comprising analysis, synthesis, and evaluation, DT has evolved into a dynamic, iterative, and nonlinear process conducive to creative problem-solving and innovation [4,5]. In educational contexts, DT is defined as "an analytic and creative process that engages a person in opportunities to experiment, create, and prototype models, gather feedback, and redesign" [6]. This learner-centered process promotes empathy, creativity, and rationality to craft human-centered solutions [7,8].

Multiple DT models have been applied in educational settings. The Stanford Design Thinking model, which includes the phases of empathize, define, ideate, prototype, and test, is particularly prevalent in K–12 and higher education [9,10]. Other widely used models include IDEO's five-phase process, Brown's inspiration–ideation–implementation framework [11], and the UK Design Council's double diamond model: discover, define, develop, and deliver [5,12]. These models focus on iterative processes and human-centered innovation, making them highly applicable in contemporary education [13,14].

DT aligns well with constructivist learning theories and embodied learning frameworks, fostering students' confidence in their creative abilities and promoting active engagement with real-world problems [7,15,16]. As a pedagogical method, DT incorporates hands-on learning, group collaboration, and inquiry-based strategies, which are central to 21st-century education [13,17]. This approach encourages students to become "change agents" who develop viable, creative solutions to complex challenges [18].

1.1. Design thinking in STEM and STEAM education

Design thinking (DT) has gained increasing relevance in science and integrated STEM/STEAM education due to its interdisciplinary alignment with science, technology, engineering, arts, and mathematics [16,19]. It fosters real-world relevance, empathy, iteration, and creative problem-solving, enhancing students' collaboration and resilience, key skills in STEM learning [7,20]. DT supports inquiry-based learning and develops both cognitive and affective competencies [13,21], helping students engage deeply in designing, testing, and improving solutions. Worldwide education systems increasingly prioritize 21st-century skills, sustainability competencies, and human-centered problem-solving [19,22]. Aligned with the United Nations Sustainable Development Goals (UNSDGs), DT fosters empathy, creativity, and critical thinking needed to address complex social and environmental issues [16,18,23,24]. Empirical research shows that engineering design processes, embedded in DT, support students' STEM practices and lifelong learning outcomes [20,25]. DT enhances early childhood STEM learning by developing collaboration and communication through iterative group work [26]. It also supports teachers in effectively designing and implementing STEM activities through design-oriented pedagogy [21,27–29]. At the tertiary level, DT strengthens inquiry-based lab investigations critical to developing scientific thinking [30,31]. Used as a problem-solving process, DT integrates engineering, social science, and arts-based tools for authentic, collaborative, and interdisciplinary learning [32,33]. Despite its growing use, fragmented DT models remain in K–12 curricula [24], indicating a need for unified pedagogical integration within STEM and STEAM contexts [13,34,35].

1.2. Research landscape and existing gaps

Given the growing interest in DT's educational applications, bibliometric and systematic reviews have become valuable tools for tracing the evolution of scholarly discourse and pedagogical innovations within this domain [36,37]. These reviews help clarify how DT is conceptualized, implemented, and researched across various disciplines. Specifically, bibliometric analyses have revealed DT's multidisciplinary diffusion and conceptual variability, reflecting its adaptability but also highlighting inconsistencies in its application [38,39]. Notably, although the literature on DT's role in teacher education and curriculum design is expanding, a significant gap remains in studies that directly assess DT's impact on science learning outcomes or its integration within STEM/STEAM pedagogies [40,41].

Despite the growing literature on DT, its scholarly application within science and integrated STEM/STEAM education remains fragmented and underexplored. Bibliometric analyses have frequently focused on DT's role across interdisciplinary domains such as business, healthcare, and general education [1,41,42], yet they seldom isolate science education as a distinct context for inquiry. Studies such as those by Hasbiyati et al. [40] and Ali and Tse [43] highlight some intersections between DT and STEM. Still, these analyses often lack detailed insight into pedagogical outcomes, student learning, or specific instructional strategies in science classrooms.

Moreover, many of the existing reviews that discuss DT in educational contexts tend to be narrative or conceptual in nature, with limited integration of bibliometric or systematic methods [44–46]. While systematic literature reviews (SLRs) such as those by Li and Zhan [24] and Panke [16] explore DT in K–12 education, they rarely focus exclusively on its implementation in science education or analyze instructional variables like theoretical frameworks, competencies, and learning outcomes. As a result, there is an absence of consolidated evidence on how DT is employed as a teaching strategy in science classrooms, including the challenges, successes, and gaps that educators encounter.

Few studies employ a dual-method approach combining bibliometric analysis with an SLR, though this integration enables both structural mapping and instructional insight [40,47,48]. Bibliometric tools like VOSviewer and Biblioshiny reveal research trends and author networks [1], but often overlook pedagogical depth [38]. SLR complements this by analyzing teaching strategies, outcomes, and theoretical frameworks. Together, they provide a comprehensive view of both the research landscape and the educational applications of DT in science education.

Consequently, a critical gap exists in the literature for a comprehensive investigation that maps the evolution and thematic distribution of DT-related research in science and integrated STEM/STEAM education and that delves into how DT is operationalized as a teaching approach in science learning environments. Addressing this dual gap is crucial for informing scholarly discourse and classroom practice on integrating DT into science education.

1.3. Purpose of the study

The purpose of this study is to comprehensively examine the role of DT in science and integrated STEM/STEAM education through a dual-method approach. It aims to (i) map the global evolution of DT-focused research using bibliometric techniques, and (ii) synthesize empirical evidence on how

DT is operationalized pedagogically within science classrooms through a systematic literature review. By doing so, the study addresses both the thematic breadth and instructional depth of DT applications, with the ultimate goal of proposing a pedagogical framework that supports context-sensitive, innovation-driven teaching and learning practices in science and STEM/STEAM education.

1.4. Research questions

1. How has global research output on DT in science and integrated STEM/STEAM education evolved, in terms of year-wise publication trends, the most prolific authors, institutions, and countries, leading journals and articles, dominant conceptual themes revealed through keyword co-occurrence, and patterns of scholarly collaboration such as co-authorship networks and bibliographic coupling?
2. How is DT implemented pedagogically in science and integrated STEM/STEAM education, considering the specific DT frameworks, tools, and techniques used; the educational levels, subjects, and geographic regions where it is applied; the research methodologies adopted; the theoretical and pedagogical foundations underpinning implementation; the competencies and student learning outcomes targeted; and the practical challenges, barriers, and enabling factors reported in empirical studies?
3. What empirically grounded pedagogical framework can be proposed to guide the effective integration of DT in science and integrated STEM/STEAM education, based on a synthesis of empirical findings, including common implementation patterns, contextual requirements, theoretical principles, core instructional phases, and practical considerations for curriculum design, teacher preparation, classroom practice, and scalability across diverse educational settings?

1.5. Objectives of the study

The present study adopts a twofold approach to examine the role of DT in science and integrated STEM/STEAM education:

i. To conduct a comprehensive bibliometric analysis of global research on DT in science and integrated STEM/STEAM education, identifying year-wise publication trends, prolific authors and institutions, influential journals and articles, emerging conceptual clusters via keyword co-occurrence, and collaboration networks through co-authorship and bibliographic coupling based on SCOPUS database.

ii. To systematically review empirical studies that explicitly implement DT as a pedagogical strategy in science/STEM education, analyzing the instructional contexts, DT frameworks, methodologies, educational levels, theoretical and pedagogical underpinnings, targeted competencies, and learning outcomes, as well as implementation challenges, enabling factors, and research gaps.

iii. To propose a pedagogical framework, the ECLIPSE-DT model, based on the synthesis of empirical evidence, articulating key phases and components of DT-informed instruction, and offering a context-sensitive guide for embedding DT into science and STEM/STEAM curricula, teacher education programs, and instructional practices.

By combining these approaches, the study aims to offer both a macro-level overview of the research landscape and a micro-level understanding of DT's pedagogical implementation in science education.

2. Methodology

2.1. Research design

This study adopted a mixed-methods design combining bibliometric mapping and SLR to investigate how DT has been utilized as a teaching strategy within science education. Integrating these two methodologies allowed for a comprehensive examination of the publication landscape and instructional practices [40,47,48]. While the bibliometric analysis identified publication trends, influential contributors, and thematic concentrations, the SLR provided more profound insights into how DT is operationalized in educational contexts, the competencies it targets, and the pedagogical frameworks that underpin its application. Combining bibliometric mapping and SLR ensures both structured coverage and deep thematic analysis. As noted by Sreenivasan and Suresh [49], rigorous protocols, when paired with reliable data sources like the Dimensions database, enhance transparency, validity, and the ability to track emerging synergies across disciplines.

2.2. Data source and search strategy

The data were retrieved from the Scopus database, selected for its comprehensive indexing of peer-reviewed literature, on April 3, 2025. Scopus is a globally trusted and curated abstract and citation database, extensively used in bibliometric analyses and SLRs due to its broad disciplinary coverage, high-quality metadata, and advanced analytical tools [50]. Compared to Web of Science, Scopus demonstrates greater source inclusivity and provides enriched metadata, robust author and institutional profiles, and highly accurate citation tracking, with precision and recall rates [50,51]. Its rigorous quality assurance framework, comprising machine learning techniques, external feedback, and human curation, helps maintain scientific integrity by excluding low-quality and predatory journals [50]. These strengths have led to Scopus being widely adopted in national research assessments, global university rankings, and SLRs across disciplines, including in fields such as healthcare, environmental sustainability, and management science [52–54].

To enhance the breadth and inclusivity of the systematic review component, two additional sources, Publish or Perish (PoP) and the Dimensions database, were also consulted. PoP was employed for its ability to extract citation data from Google Scholar and other databases, offering access to grey literature and broader coverage of interdisciplinary works [55,56]. The Dimensions platform was selected to complement Scopus's indexing by capturing additional open-access and policy-relevant publications, as it is known for its comparable citation coverage and reliability in bibliometric research [54]. Together, these databases provided a more comprehensive and diverse dataset for the SLR.

In the study, a structured search query was designed to capture publications connecting DT with science education: TITLE-ABS-KEY (("design thinking") AND ("Science" OR "STEM" OR "STEAM" OR "physics" OR "chemistry" OR "biology" OR "environmental science" OR "earth science" OR "life science" OR "physical science") AND ("teach*" OR "educat*" OR "learn*" OR "instruct*" OR "pedagog*")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (

DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")). The search was limited to English-language journal articles and applied to titles, abstracts, and keywords.

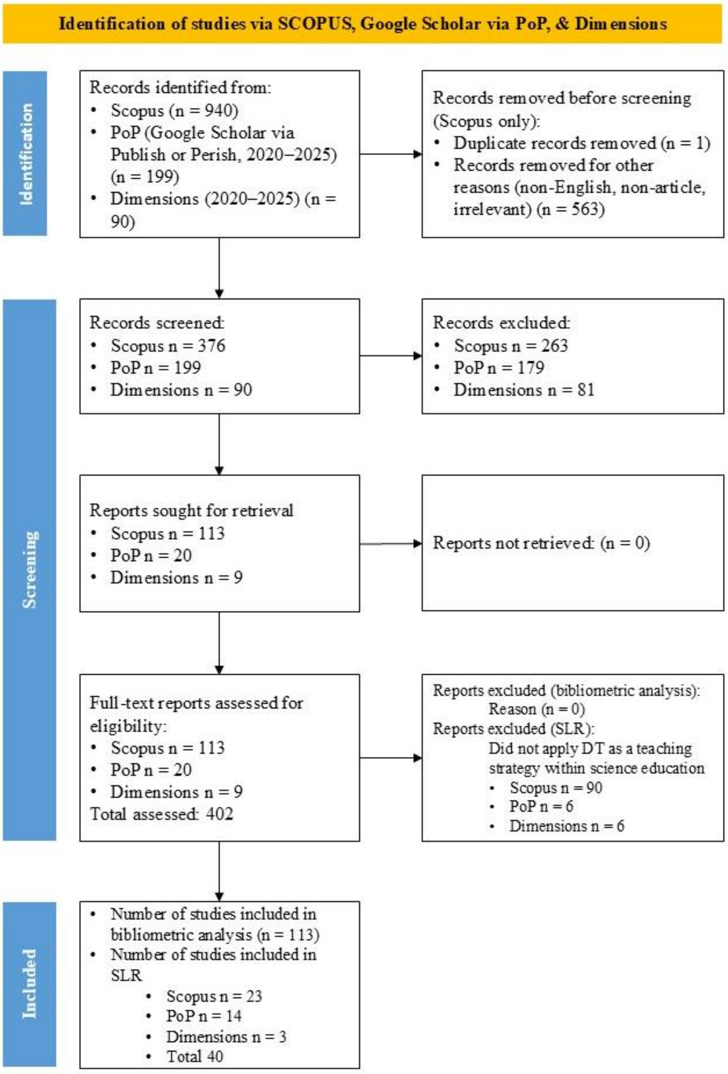

Figure 1. PRISMA flow diagram.

2.3. Inclusion and exclusion criteria

Guided by the PRISMA 2020 protocol, a multi-stage filtering process was applied to identify studies relevant for bibliometric analysis and SLR (Figure 1). Clear and differentiated inclusion and exclusion criteria were established for each phase to ensure relevance, methodological consistency, and alignment with the study's objectives.

For the bibliometric analysis, studies were included if they referred to DT in the context of science education or integrated STEM/STEAM education, regardless of whether DT was conceptually discussed or practically implemented. The aim at this stage was to map the overall research landscape, so broader inclusion was permitted. Articles were considered if they were peer-reviewed, published in English, and indexed as journal articles. Studies not meeting these basic publication criteria, such as non-English documents, non-article formats, or those outside the scope of science/STEM education, were excluded.

For the SLR, more stringent inclusion criteria were applied. Studies were selected only if they explicitly implemented DT as a teaching or instructional strategy within science education or STEM/STEAM settings where science played a central role. Eligible studies needed to describe instructional practices, interventions, or learning activities that aligned with one or more phases of the DT process. Furthermore, they were required to report on educational outcomes, developed competencies, or impacts on learners or educators. Studies were excluded if DT was only referenced conceptually without actual application in the classroom, or if the educational context did not clearly involve science (e.g., studies focused solely on mathematics or engineering). Other exclusions included non-English publications and non-journal formats.

These criteria were applied systematically across the three data sources—Scopus, Google Scholar via PoP, and Dimensions—to ensure that only relevant and pedagogically grounded studies were retained for in-depth analysis. Twenty-three studies, pooled from Scopus, were selected for the SLR based on more stringent inclusion criteria. To enhance coverage, additional searches were conducted on July 28, 2025, using Publish or Perish (PoP) and the Dimensions database. The PoP search, limited to the period 2020–2025, initially yielded 199 results, from which 14 studies were selected after duplicate removal and close reading. The Dimensions database yielded 90 studies, from which 3 additional studies were selected. This resulted in a final SLR dataset of 40 studies.

For consistency and clarity, the term “science education” is used throughout this article to encompass both standalone science instruction and interdisciplinary STEM/STEAM approaches where science is a central component. Studies focusing solely on other STEM/STEAM subjects without an explicit science focus were not included.

2.4. Bibliometric analysis tools and techniques

To identify trends, author networks, and thematic concentrations in the DT–science/STEM literature, bibliometric mapping techniques were applied using two visualization and analysis tools. Biblioshiny, a web interface for the Bibliometrix R-package, was used to compute bibliometric indicators. BibTeX data were processed using RStudio and uploaded into Biblioshiny to analyze publication trends, citation metrics, author productivity, source impact, and keyword frequencies. VOSviewer was employed to construct co-authorship networks, co-citation maps, and keyword co-occurrence visualizations, enabling the identification of research clusters and collaboration patterns within DT and science education research.

2.5. Systematic literature review procedure

The SLR phase followed the PRISMA 2020 protocol and involved rigorous study selection, structured data extraction, and thematic analysis of 40 empirical studies to derive cross-cutting patterns in DT-based instructional practice. This procedure followed a structured path for study selection, data extraction, and thematic synthesis. The 40 studies included in this phase were drawn from Scopus, PoP, and Dimensions, based on inclusion criteria.

Data were independently extracted by the researchers, with discrepancies resolved through collaborative discussion. The analysis focused on six thematic dimensions: (1) DT implementation strategy, (2) instructional context and methodology, (3) theoretical or pedagogical frameworks, (4) learning outcomes and competencies, (5) challenges and enabling factors, and (6) research gaps and future directions. To support consistent analysis and cross-study comparison, each study was coded using a structured matrix that included bibliographic metadata (publication year, authors, title, journal, DOI), study focus and context (subject area, education level, country/region), methodological features (design, sample, sample size, duration), implementation details (DT framework used, instructional tools and techniques), theoretical foundations (underlying theories and pedagogical models), and research findings (key variables studied, reported challenges and enablers, study limitations, and author-recommended future directions).

Extracted data were analyzed thematically to identify patterns and synthesize insights across diverse educational settings. These findings informed the construction of the ECLIPSE-DT pedagogical framework, comprising empathic engagement, contextual integration, learner agency, inquiry orientation, process scaffolding, scalability planning, and evaluation mechanisms, which reflect recurring instructional principles and strategic design elements for applying DT in science and integrated STEM/STEAM education.

3. Results

The results of this study are presented in two main parts, reflecting the dual-method approach adopted. The first part reports the bibliometric findings derived from 113 Scopus-indexed publications on DT in science and integrated STEM/STEAM education. This includes analyses of publication trends, leading authors and institutions, keyword co-occurrences, and international collaboration patterns. These results provide a macro-level overview of the research landscape. The second part presents the thematic findings from an SLR of 40 empirical studies, synthesizing insights on how DT is implemented as a pedagogical strategy in science education. These findings are organized across six analytical categories: implementation strategies, instructional context and methodology, theoretical and pedagogical frameworks, learning outcomes and competencies, challenges and enabling factors, and research gaps and future directions. Together, the two components offer both breadth and depth in understanding the pedagogical applications and research trends of DT in science education.

3.1. Bibliometric results

3.1.1. Publication trends: Year-wise distribution, growth rate

The annual distribution of publications related to the application of DT in science education reveals a significant upward trend over the past decade. As shown in Figure 2, the earliest publication appeared in 2011, followed by sporadic output in the subsequent years. A steady increase began in 2018, with noticeable growth from 2020 onward. The number of publications peaked in 2024, reaching a total of 27 articles, marking the highest annual contribution within the dataset. This growth reflects the increasing academic interest in DT as an innovative pedagogical strategy in science-related disciplines.

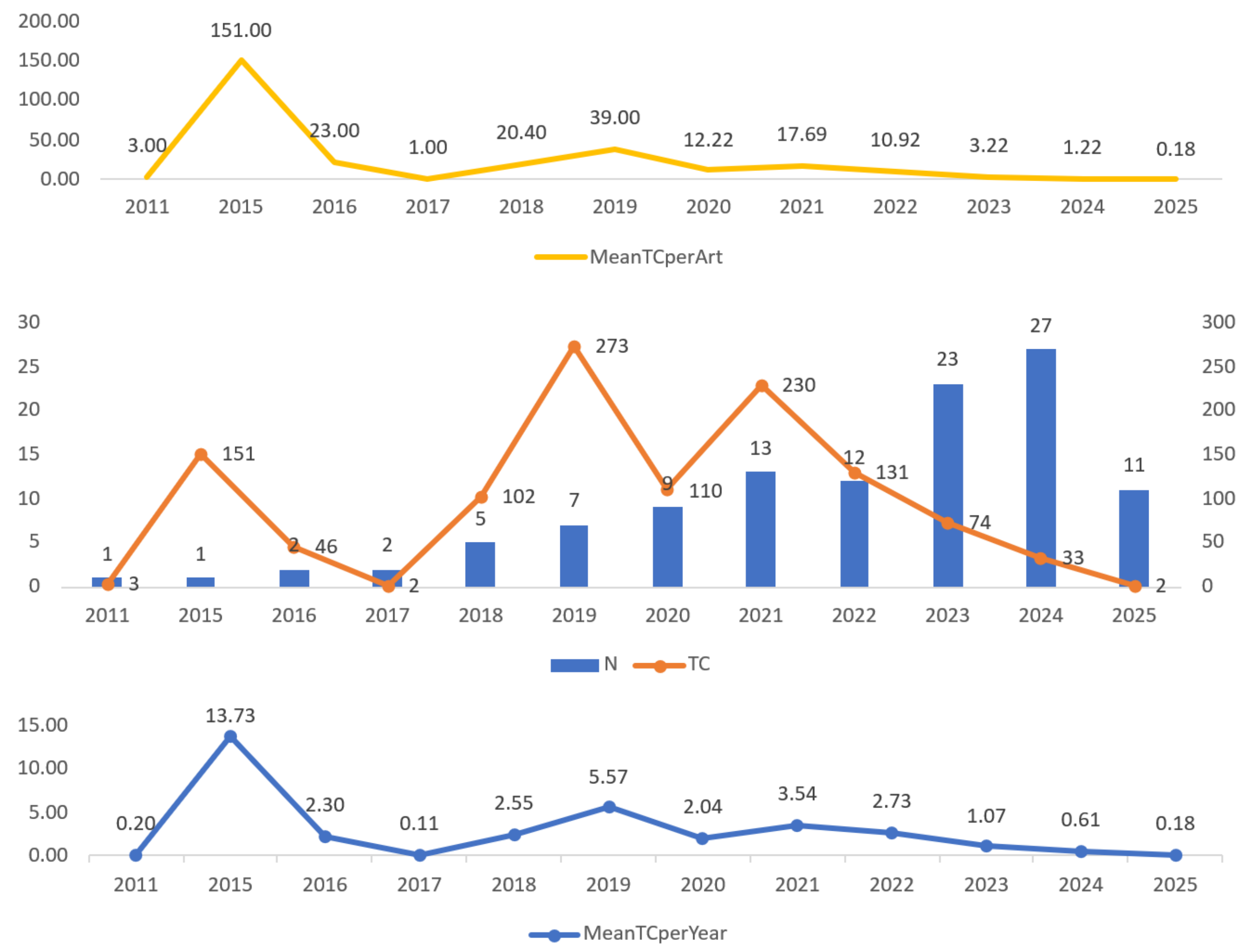

Figure 2. Citation metrics per year for publications on design thinking in science education.

Note: MeanTCperArt = average total citations per article; MeanTCperYear = average citations per article per year; TC = total citations; N = number of articles.

Citation metrics also varied notably over time. As depicted in Figure 2, the average total citations per article (MeanTCperArt) peaked in 2015, indicating the presence of highly influential articles published during that year, despite the low number of publications. Similarly, the average citation per year (MeanTCperYear) showed fluctuations across the years, reflecting differences in scholarly attention. The high citation count for earlier years is partly due to the greater time span available for citations to accumulate. Recent years (2023–2025), although characterized by higher publication volume, naturally exhibit lower citation averages due to their recency and limited citation window.

The increasing publication rate combined with growing thematic interest suggests that DT is gaining recognition in the domain of science education research, particularly in the context of competency-based and innovation-driven instructional strategies.

3.1.2. Authorship analysis: Prolific authors and institutional and national productivity

Figure 3. Top 10 authors by number of articles and total citations in design thinking and science education.

Note: Bars represent the number of articles published by each author. The line and points indicate total citations per author, scaled to align with a secondary Y-axis on the right.

The authorship analysis revealed a number of key contributors actively publishing on DT in science education. Ladachart L. was the most prolific author, with four publications across prominent journals and a growing citation record. Phothong W. and Han J. followed closely, each with three publications contributing to the development of DT-integrated pedagogies (Figure 3).

High citation counts were observed for several authors despite fewer publications. English L.D. and King D.T. each published a single article, yet both works received 151 citations, indicating high impact. Similarly, Kuo H-C. (2 articles, 131 citations) and Tseng Y-C. (1 article, 125 citations) showed strong influence in the field.

Other active contributors include Kijima R. (3 articles, 93 citations), Anariba F. (2 articles, 31 citations), and Alvarez V. (2 articles, 17 citations). These authors have shown continued engagement in exploring and documenting the use of DT to enhance science learning outcomes.

This spread of both high-impact and high-output authors reflects a healthy balance of sustained contribution and standout individual works within the evolving literature on DT in science education.

The analysis of institutional affiliations revealed that a diverse set of universities contributed significantly to research on DT in science education (Figure 4). Purdue University emerged as the most productive institution, contributing a total of 11 publications. Universiti Teknologi Malaysia followed this with 8 articles, reflecting strong regional engagement with design-based approaches to teaching and learning.

Two institutions, National Taiwan Normal University and the University of Ibadan, each contributed 7 publications, indicating growing research activity in Asia and Africa, respectively.

Duke University also featured among the top affiliations, with 6 publications contributing to shaping the discourse on innovation and pedagogy in science education.

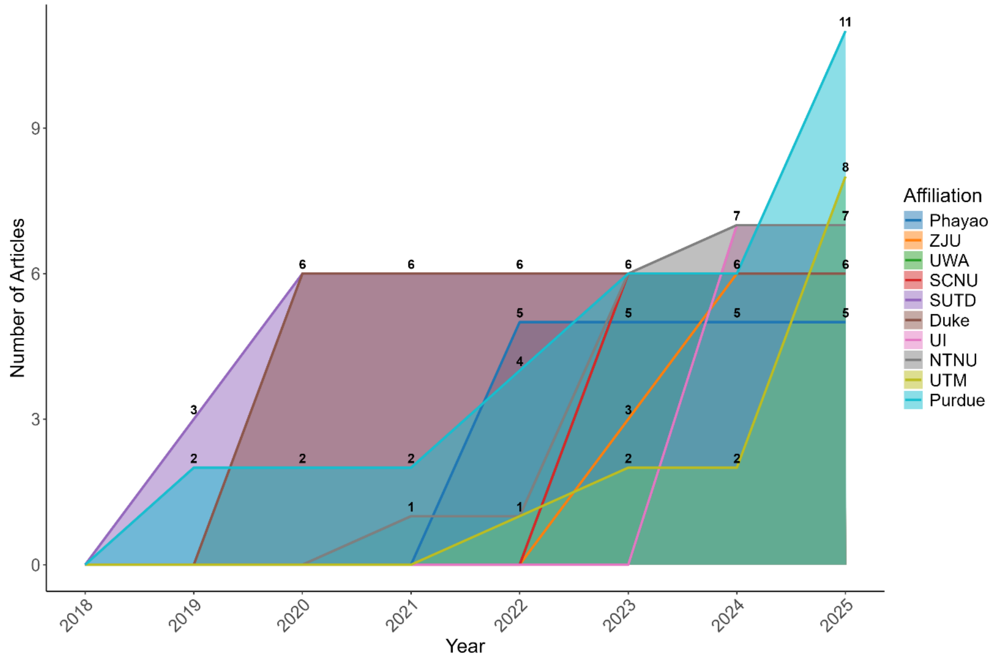

Figure 4. Academic publication growth among leading institutions.

Note: The figure shows the cumulative number of articles published by institutions from 2018 to 2025. Affiliation short forms: Phayao, University of Phayao; ZJU, Zhejiang University; UWA, University of West Attica; SCNU, South China Normal University; SUTD, Singapore University of Technology and Design; Duke, Duke University; UI, University of Ibadan; NTNU, National Taiwan Normal University; UTM, Universiti Teknologi Malaysia; Purdue, Purdue University.

Table 1. Top 10 countries by number of articles and total citations.

Country	N	TC	Average article citations
USA	90	211	11.7
CHINA	47	209	23.2
MALAYSIA	29	5	0.7
AUSTRALIA	27	218	27.2
BRAZIL	19	-	-
INDONESIA	15	6	1.5
THAILAND	15	30	10
TURKEY	14	73	14.6
CANADA	13	84	21
GREECE	11	3	1.5

Note: N = Number of articles calculated based on authors' country; TC = total citations. Countries are ranked by the number of publications. Citation data is up to 2024. Average article citations were calculated as TC/N.

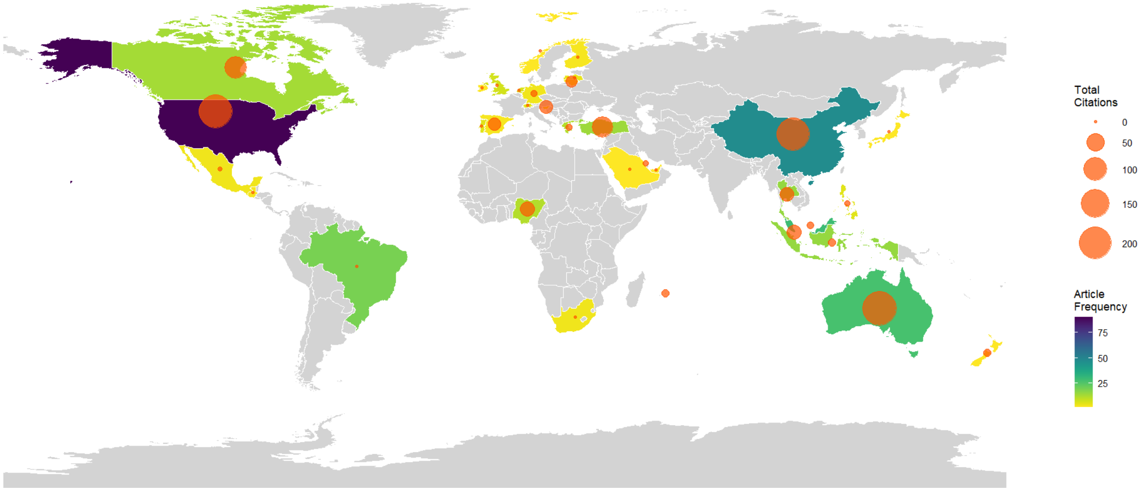

Figure 5. Global distribution of scientific articles and citations by country.

Note: The map displays scientific production across countries. Color intensity represents the number of articles published per country (darker colors indicate higher article counts). Orange circles represent the total number of citations received, with larger circles indicating higher citation counts.

The country-level analysis revealed that the United States leads the research landscape on DT in science education, contributing the highest number of publications (N = 90) and accumulating a total of 211 citations (Table 1, Figure 5). China ranks second in publication volume (N = 47) but demonstrates a significantly higher average citation impact (23.2), closely followed by Australia (N = 27, 218 citations), which records the highest average article citations (27.2). These figures reflect strong academic visibility and influence for both countries, despite lower publication counts than in the U.S.

Countries such as Turkey (N = 14, TC = 73) and Canada (N = 13, TC = 84) also show robust engagement, with above-average citation rates (14.6 and 21, respectively). Southeast Asian countries, including Thailand (N = 15, TC = 30) and Indonesia (N = 15, TC = 6), contribute moderate publication counts, though citation impacts vary (Figure 5). Despite a higher number of articles (N = 29), Malaysia shows low citation influence with only 5 total citations (0.7 average), indicating limited academic reach. Greece (N = 11, TC = 3) also reflects minimal citation impact.

These findings show how DT research has spread globally, with major contributions coming from North America, East Asia, and Asia-Pacific (Figure 5). The citation patterns reflect how much is being published and the quality and impact of the work, highlighting the increasing international interest in using DT as a powerful and innovative teaching approach in science and STEM education.

3.1.3. Source analysis: Leading journals and articles

The journal-level analysis revealed the most influential publication venues contributing to the literature on DT in science education. The *International Journal of Technology and Design Education* ranked highest with 10 articles, receiving 86 citations (Figure 6). This journal also demonstrated strong bibliometric performance with an h-index of 4, g-index of 9, and m-index of 1.00, reflecting both productivity and consistent citation impact over time.

Frontiers in Education and the *EURASIA Journal of Mathematics, Science and Technology Education* each contributed 5 articles, with 18 and 24 total citations, respectively. Both journals showed modest influence with h- and g-indexes of 1 and 4, and m-index values of 0.167, indicating early-stage but growing scholarly attention.

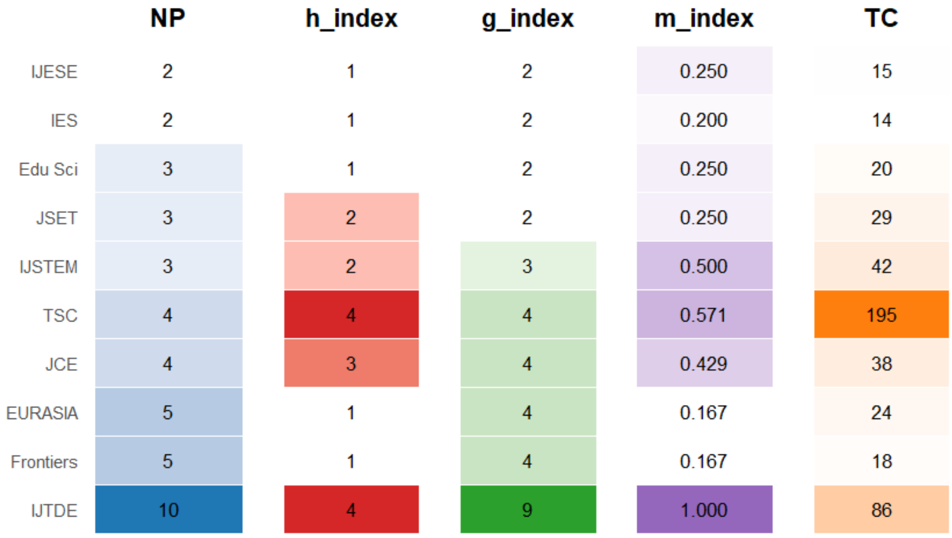

Figure 6. Heatmap of bibliometric metrics across top 10 journals.

*Note: This heatmap displays five bibliometric variables across ten journals. Variables include: NP (number of publications), h-index, g-index, m-index, and TC (total citations). Journals represented are IJTDE (*International Journal of Technology and Design Education*), Frontiers (*Frontiers in Education*), EURASIA (*EURASIA Journal of Mathematics, Science and Technology Education*), JCE (*Journal of Chemical Education*), TSC (*Thinking Skills and Creativity*), IJSTEM (*International Journal of STEM Education*), JSET (*Journal of Science Education and Technology*), Edu Sci (*Education Sciences*), IES (*International Education Studies*), and IJESE (*International Journal of Environmental & Science Education*). Each cell is color-coded based on the relative magnitude of the metric within its column.*

The *Journal of Chemical Education*, publishing 4 articles with 38 citations, demonstrated a solid h-index of 3 and m-index of 0.429, suggesting its work in this area has gained moderate and steady recognition. In contrast, *Thinking Skills and Creativity*, also with 4 articles, recorded an exceptional 195 citations, with an h-index of 4, g-index of 4, and the highest m-index (0.571) among the top five, indicating rapid and impactful academic engagement.

These top journals are joined by others such as *International Journal of STEM Education*, *Journal of Science Education and Technology*, and *Education Sciences*, which, although publishing fewer papers, have added depth to the field with focused contributions and steady citation traction. Their h- and g-index values typically ranged between 1 and 3, reflecting early but meaningful participation in the evolving DT-in-science education research landscape.

The data show a balance between high-volume and highly influential journals, with some sources excelling in productivity and citation performance. These journals form the core publication platforms driving scholarly discourse on integrating DT into science education contexts.

Analyzing the most globally cited studies highlights key contributions that have shaped the application of DT in science and integrated STEM/STEAM education. These studies span empirical investigations, conceptual models, and curriculum-level innovations across diverse learning contexts.

Topping the list is English & King (2015) with "STEM learning through engineering design: fourth-grade students' investigations in aerospace" (151 citations), which established a foundation for integrating engineering design challenges into K–12 STEM education. Kuo et al. [57] in

"Promoting College Student's Learning Motivation and Creativity through a STEM Interdisciplinary PBL Human-Computer Interaction System Design and Development Course" (125 citations) has the highest citation rate recorded, emphasizing creativity and motivation in higher education.

Cook & Bush [7] offered "Design thinking in integrated STEAM learning: Surveying the landscape and exploring exemplars in elementary grades" (91 citations), providing a widely cited framework for DT-STEAM integration. Kijima et al. [58] in "Using design thinking to cultivate the next generation of female STEAM thinkers" (62 citations), and Wu et al. (2019) with "Scaffolding design thinking in online STEM preservice teacher training" (53 citations) demonstrate DT's applicability in formal curricula and teacher education.

Yalçın & Erden [59] explored "The Effect of STEM Activities Prepared According to the Design Thinking Model on Preschool Children's Creativity and Problem-Solving Skills" (51 citations), while McAuliffe [60] discussed foundational concepts in "The potential benefits of divergent thinking and metacognitive skills in STEAM learning" (41 citations).

Completing the list are Chiu et al. [29] with "Teacher Professional Development on Self-Determination Theory–Based Design Thinking in STEM Education" (40 citations), Simeon et al. [61] with "Effect of design thinking approach on students' achievement in some selected physics concepts in the context of STEM learning" (31 citations), and Marks & Chase [62] with "Impact of a prototyping intervention on middle school students' iterative practices and reactions to failure" (31 citations). Together, these works provide a rich foundation for ongoing DT-based research in science education.

3.1.4. Keyword co-occurrence and clusters

To map the intellectual structure of research at the intersection of DT and science, a keyword co-occurrence analysis was performed using VOSviewer. The analysis used author keywords with a minimum threshold of two occurrences, resulting in a network of 51 keywords forming 14 distinct clusters. These clusters, derived using the Louvain clustering algorithm and association strength normalization, were visualized with a color-coded map where each cluster represents a coherent thematic grouping (Figure 7, Table 2).

Cluster 1, the largest and most cited, centered around creativity, arts, engineering, and project-based learning (PBL), integrates creative thinking and problem-solving within STEM contexts. With an average citation count of over 40 and connections to technology, science, and teacher education, this cluster focuses on applying DT to foundational science learning enriched by design, arts, and experiential learning. Cluster 2, anchored by design thinking, collaboration, and self-directed learning, emerged as the most central in the network, linking to nearly every other cluster. This reflects the central methodological role that DT plays across various educational settings, with the highest level of connectivity among all clusters (44 links; link strength = 122). Notably, the publications in this cluster are relatively recent (average year = 2023), highlighting the growing interest in collaborative, student-centered pedagogies.

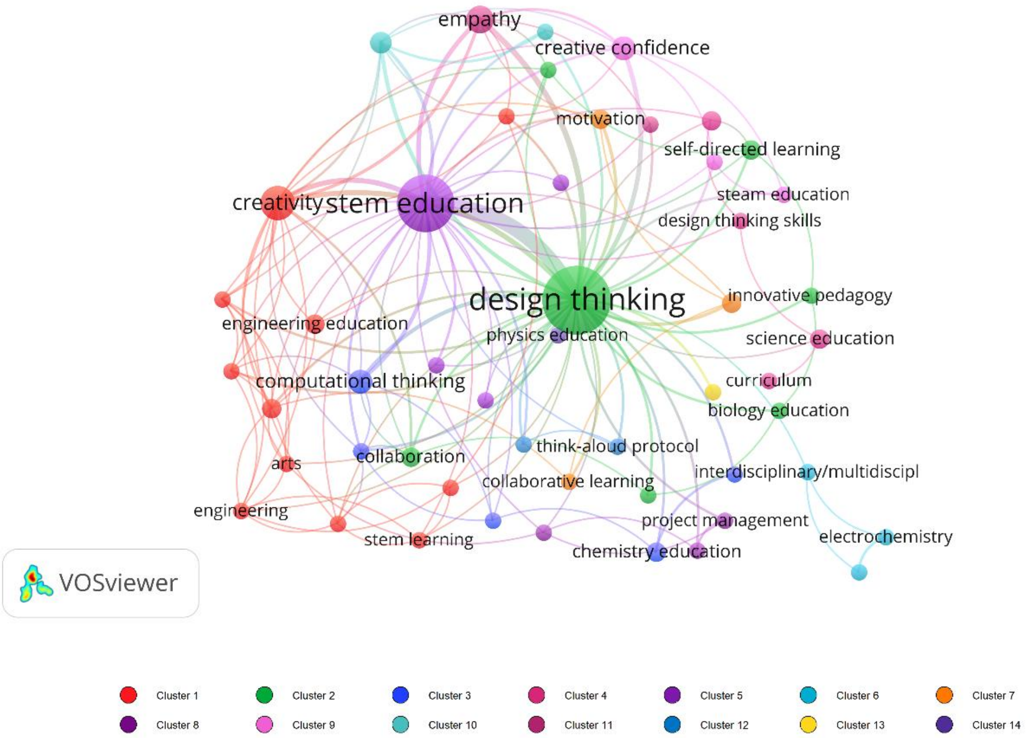

Figure 7. Keyword co-occurrence network.

Note: The network includes 51 author keywords that occurred at least twice across the dataset, clustered into 14 thematic groups using the Louvain algorithm. Node size indicates keyword frequency, and line thickness represents co-occurrence strength. Cluster colors denote distinct research themes.

Cluster 3 focuses on computational thinking, self-efficacy, and chemistry education, representing a meaningful intersection between technology integration and science instruction. It also records the highest average normalized citation score, suggesting that although the research is emerging, it is already making a significant impact. Cluster 4 focuses on curriculum, pre-service teachers, and science education, representing teacher preparation and curriculum design. This cluster features established yet evolving interest, with the curriculum receiving high citations (51). Cluster 5 centers on STEM education, makerspaces, and tertiary education, forming the second-largest hub in the network, highlighting systemic DT integration in higher education and institutional STEM reform.

Table 2. Cluster-wise co-occurring keywords on design thinking in science education.

Cluster	Keywords
Cluster 1	Arts, creativity, elementary school, engineering, engineering education, problem solving, project-based learning (PBL), science, STEM learning, teacher education, technology
Cluster 2	Design thinking, biology education, collaboration, innovative pedagogy, project-based learning, secondary education, self-directed learning
Cluster 3	Chemistry education, computational thinking, innovation competencies, self-efficacy, TPACK
Cluster 4	Curriculum, design thinking skills, pre-service teachers, science education
Cluster 5	Higher education, makerspaces, STEM education, tertiary education
Cluster 6	Electrochemistry, high school/introductory chemistry, interdisciplinary/multidisciplinary
Cluster 7	Collaborative learning, middle school, motivation

Cluster	Keywords
Cluster 8	Experiential learning, professional development, project management
Cluster 9	Creative confidence, creative self-efficacy, STEAM education
Cluster 10	Creative problem-solving, IoT
Cluster 11	Empathy, innovation
Cluster 12	Shared practice, think-aloud protocol
Cluster 13	Middle school students
Cluster 14	Physics education

Cluster 6 is a small, focused group linking electrochemistry, high school chemistry, and interdisciplinary education, reflecting content-specific applications of DT. Cluster 7 targets middle school, motivation, and collaborative learning, emphasizing learner engagement and emotional factors. The keyword *motivation* averages 25 citations, suggesting a strong interest in its relationship with DT. Cluster 8, consisting of experiential learning, project management, and professional development, reflects practice-oriented research geared toward educators and classroom innovation.

Cluster 9 centers on affective outcomes, featuring terms like *creative confidence*, *creative self-efficacy*, and *STEAM education*. The keywords in this cluster connect creativity with learner identity and emotional growth, reflecting a rising interest in the psychological aspects of DT. Cluster 10 is anchored in themes such as *creative problem-solving* and the *Internet of Things (IoT)*, blending emerging technologies with educational design. However, this cluster shows limited citation impact and consists mainly of older research, suggesting its influence may be waning. Cluster 11 combines keywords like *empathy* and *innovation*, emphasizing DT's foundation in human-centered design. With a relatively recent average publication year and moderate citation levels, this cluster highlights DT's role in fostering emotional intelligence and innovation-oriented competencies.

Clusters 12–14 are smaller and more specialized. Cluster 12 includes *shared practice* and *think-aloud protocol*, reflecting methodological studies on observing and assessing DT in action. Clusters 13 and 14 are singleton clusters, with *middle school students* and *physics education*, respectively. While marginal in size and connectivity, they highlight niche research spaces that may evolve further.

Network-wide, the strongest connections include design thinking to STEM education (link strength = 32), followed by design thinking to empathy (7), and design thinking to creativity (6). These connections reflect DT's role as a conceptual anchor linking pedagogy, emotion, and disciplinary integration. Chronologically, the field is expanding toward affective and future-ready themes (empathy, innovation, computational thinking), while foundational applications (problem-solving, PBL) remain well-cited. This analysis underscores how DT has evolved into a multifaceted framework that connects diverse domains of science education, with increasing emphasis on human-centered, technology-integrated, and creative pedagogical practices.

3.1.5. Collaboration patterns

3.1.5.1. Country collaboration patterns

The country collaboration analysis highlights a vibrant and globally connected research landscape, with 22 countries contributing to the bibliographic network (Figure 8). The United States stands out as the most prolific and central contributor, producing the highest number of publications (26), receiving the most citations (308), and exhibiting the strongest collaborative ties (link strength = 1352). Other key countries include Australia, Canada, China, and Turkey, each forming significant collaborative hubs with high total link strengths of 443, 596, 920, and 586, respectively. Interestingly, Hong Kong, despite contributing a modest number of publications (7), demonstrated one of the densest international collaboration networks (link strength = 980), underscoring its strategic role in global research partnerships.

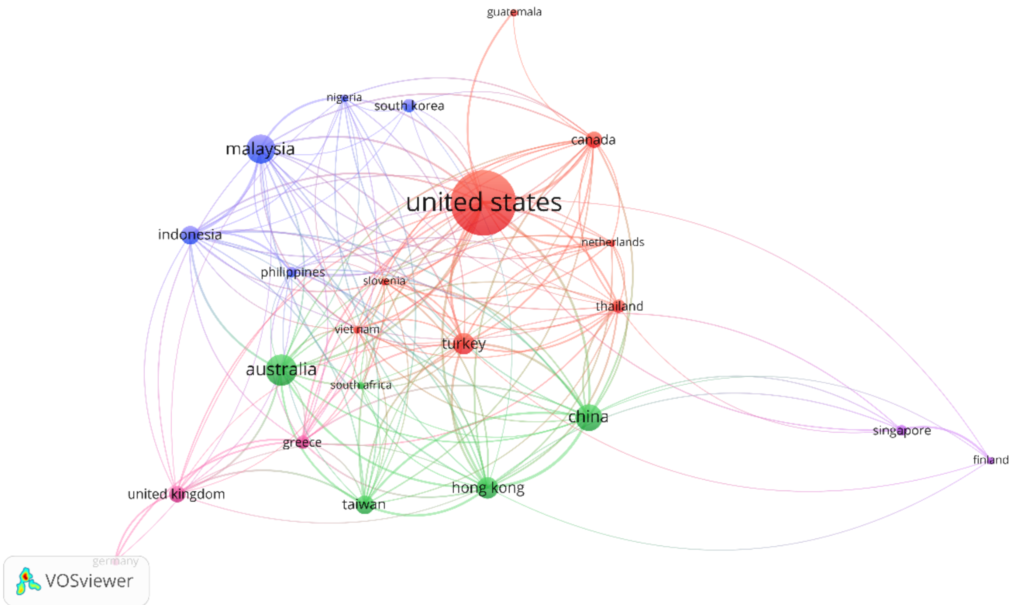

Figure 8. Country-level co-authorship network in DT–STEM education studies.

Note: This illustrates international collaboration among countries contributing to DT in STEM/STEAM education. Node size represents the number of documents authored by a country, and line thickness indicates the strength of co-authorship links. Colors represent collaboration clusters. Created using VOSviewer.

A distinct pattern of Asia-Pacific collaboration was evident in regional dynamics, primarily within Cluster 2, which included Australia, China, Hong Kong, Taiwan, and South Africa (Table 3). These countries showed strong mutual linkages and high citation impacts, with Taiwan averaging the highest citations per document (30.83). Cluster 1, the largest by document count, encompassed North American and European countries such as the United States, Canada, Turkey, the Netherlands, and Thailand, and was characterized by broad intercontinental collaboration and citation strength.

Table 3. Countries grouped by collaboration clusters**.**

Cluster	Countries
Cluster 1	Canada, Guatemala, Netherlands, Slovenia, Thailand, Turkey, United States, Vietnam
Cluster 2	Australia, China, Hong Kong, South Africa, Taiwan
Cluster 3	Indonesia, Malaysia, Nigeria, Philippines, South Korea
Cluster 4	Germany, Greece, United Kingdom
Cluster 5	Finland, Singapore

Emerging countries such as Malaysia, Indonesia, Nigeria, and the Philippines formed Cluster 3, featuring the newest publications (average year 2022–2024) and representing a rising Southeast Asian scholarly presence. Although citation impact is growing, these countries demonstrate increasing collaboration and publication volume, particularly Malaysia (10 documents, link strength

543). European countries, including Germany, Greece, and the United Kingdom, are grouped into Cluster 4, with more established publications and moderate influence. Meanwhile, Singapore and Finland formed the smallest cluster (Cluster 5), characterized by niche research focus and high specialization.

Top collaborative country pairs included Canada–United States (link strength 386), China–Hong Kong (371), Indonesia–Malaysia (268), and United States–Turkey (142), indicating both regional and intercontinental partnerships. The analysis affirms that while North America and East Asia dominate in volume and centrality, Southeast Asia is emerging rapidly as a collaborative and contributing region.

3.1.5.2. Author collaboration patterns

The author-level co-authorship network sheds light on the structural dynamics and scholarly partnerships shaping DT research in science and integrated STEM/STEAM education (Figure 9, Table 4). This analysis identified 27 unique authors, organized into eight distinct clusters that reveal patterns of recurring collaboration and intellectual synergy. These clusters represent a mix of closely connected dyads and wider collaborative teams, highlighting strong individual partnerships and broader research communities that collectively contribute to the field's evolving knowledge base.

Cluster 1 emerged as the most expansive, comprising eight researchers: Chen, Juanjuan; Cook, Kristin L.; Kijima, Rie; Kuo, Hsu-Chan; Rahmawati, Yuli; Tae, Jinmi; Topçu, Mustafa Sami; and Yang-Yoshihara, Mariko. The strongest collaboration in this cluster, and indeed one of the most prominent in the entire network, was between Kijima and Yang-Yoshihara, with a link strength of 198, underscoring a well-established scholarly partnership. This cluster demonstrated dense internal linkages, signifying a highly productive collaborative ecosystem.

Cluster 2 included Alvarez, Valentina; Asturias, Gabriela; Dotson, Mary Elizabeth; and Ramanujam, Nirmala. This group displayed uniform and balanced collaboration patterns, with the strongest tie between Alvarez and Asturias (link strength = 59), indicating a close and cohesive research alliance. Similarly, Cluster 3 comprised Anariba, Franklin, Hölttä-Otto, Katja, and Tan, Shun Yu, with a notable link strength of 67 between Anariba and Hölttä-Otto. These authors have contributed consistently to the field, often focusing on engineering and technical education contexts.

Table 4. Clusters in the author-level co-authorship network.

Cluster	Authors	Notable collaboration	Link strength
Cluster 1	Chen, Juanjuan; Cook, Kristin L.; Kijima, Rie; Kuo, Hsu-Chan; Rahmawati, Yuli; Tae, Jinmi; Topçu, Mustafa Sami; Yang-Yoshihara, Mariko	Kijima, Rie & Yang-Yoshihara, Mariko	198
Cluster 2	Alvarez, Valentina; Asturias, Gabriela; Dotson, Mary Elizabeth; Ramanujam, Nirmala	Alvarez, Valentina & Asturias, Gabriela	59
Cluster 3	Anariba, Franklin; Hölttä-Otto, Katja; Tan, Shun Yu	Anariba, Franklin & Hölttä-Otto, Katja	67
Cluster 4	Luo, Ma; Sun, Daner; Zhu, Liying	Luo, Ma & Sun, Daner	151
Cluster 5	Ladachart, Luecha; Phothong, Wilawan; Radchanet, Visit	Ladachart, Luecha & Phothong, Wilawan	189
Cluster 6	Avsec, Stanislav; Ferk Savec, Vesna	Ferk Savec, Vesna & Avsec, Stanislav	226

Cluster 7	Han, Jung; Sung, Euisuk	Han, Jung & Sung, Euisuk	132
Cluster 8	Honra, Joelash R.; Monterola, Sheryl Lyn C.	Honra, Joelash R. & Monterola, Sheryl Lyn C.	51

Emerging research voices were observed in Cluster 4, which consisted of Luo, Ma; Sun, Daner; and Zhu, Liying. The collaboration between Luo and Sun (link strength = 151) suggests an intensifying partnership, characterized by recent and focused scholarly contributions. Cluster 5, formed by Ladachart, Luecha; Phothong, Wilawan; and Radchanet, Visit, demonstrated strong internal cohesion, with the highest dyadic collaboration being between Ladachart and Phothong (link strength = 189), reflecting deep-rooted academic synergy.

The strongest partnership identified within the co-authorship network was in Cluster 6, featuring Avsec, Stanislav and Ferk Savec, Vesna, whose sustained collaboration achieved an impressive link strength of 226. This indicates a prolific and long-standing academic relationship, positioning them as a key contributor dyad in the field. Cluster 7 includes Han, Jung and Sung, Euisuk, with a link strength of 132, underscoring the value of consistent thematic co-authorship over time. Meanwhile, Cluster 8, comprising Honra, Joelash R. and Monterola, Sheryl Lyn C., represents an emerging research partnership, with a respectable link strength of 51, signaling the entry of new voices into the DT in education discourse.

Together, these collaboration patterns illustrate a field characterized by continuity and innovation. The network reveals how enduring partnerships act as intellectual anchors, shaping the foundational discourse, while newer collaborations inject fresh ideas and broaden the scope of DT research in science and STEM education.

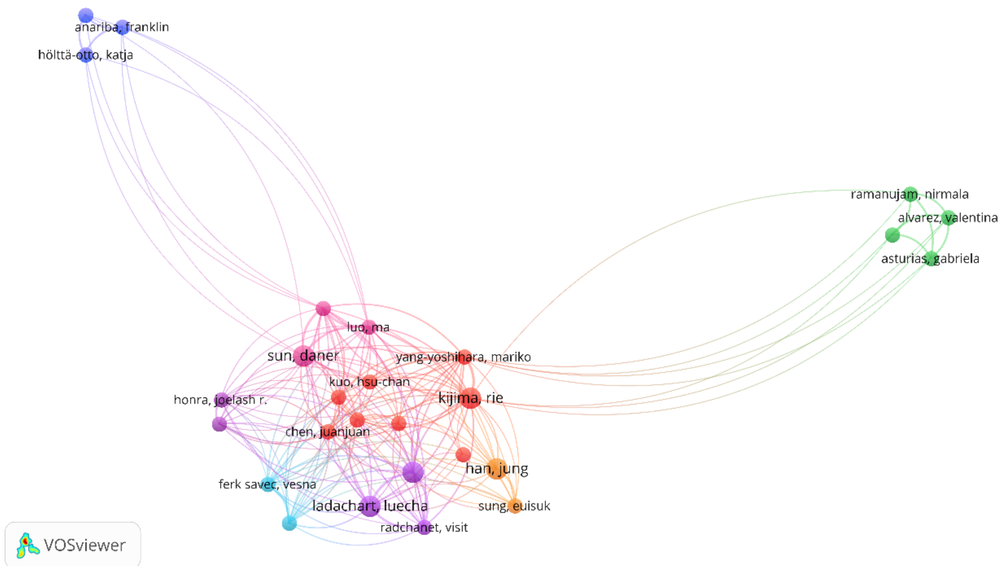

Figure 9. Author-level co-authorship network in DT–STEM education studies.

Note: This network displays the co-authorship relationships among the most active authors in the DT-science education literature. Larger nodes signify higher publication output or co-authorship centrality. Links denote co-authored publications, and thicker lines indicate stronger collaboration. Clusters denote closely collaborating author groups. Visualization generated using VOSviewer.

3.2. Results from systematic literature review

3.2.1. Implementation patterns of DT in science education

This section analyses how DT was conceptualized and operationalized across the reviewed studies, with emphasis on frameworks employed, subject areas addressed, implementation duration, and, most critically, the pedagogical tools and techniques that enabled DT-based instruction.

The most widely employed framework was the Stanford d.school 5-stage model (2009), featured in 27 studies (Figure 10). Some adopted the model as is [63,64], while others adapted it for local relevance or deeper iteration. For instance, Honra and Monterola [65] extended the empathy and prototyping phases to foster resilience among biology students. Annetta et al. [66] integrated the model within a semester-long Earth science program for pre-service teachers, using it to structure classroom design challenges.

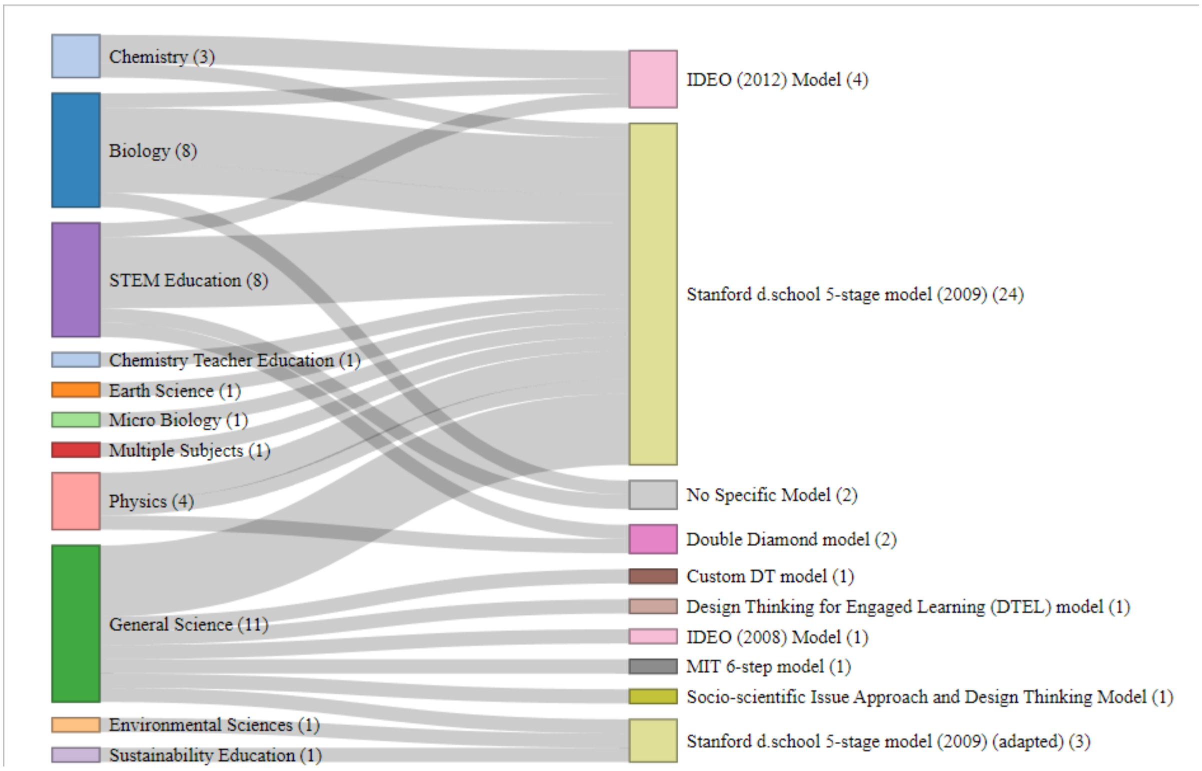

Figure 10. Distribution of design thinking models used in science education studies.

Alternative frameworks included the IDEO model (2012), noted in Al-Muqbil [67] and Aris et al. [68], and the Double Diamond model, used in higher education physics and sustainability courses [69]. Other studies developed custom models, such as Galoyan et al. [70], who combined design and sports science, or adopted hybrid models such as Pohl et al. [71], who merged DT with systems thinking in a sustainability education context. A small number of studies applied DT principles without citing a formalized model.

Across the studies, DT was implemented using a variety of hands-on, collaborative, and design-oriented tools. A core technique was the use of reflective journals and video reflections [63,72–74], allowing learners to track idea evolution and engage in metacognitive reflection. Design documents, project worksheets, and innovation checklists [66,68,75] structured the iterative process of ideation and prototyping.

Focus group discussions, empathy interviews, and co-design workshops were frequently used to elicit needs and refine student designs with peer or stakeholder input [69,76]. Lesson plans, scenario-based questions, and design thinking rubrics [61,73] helped teachers scaffold and evaluate creativity, feasibility, and user-centeredness in student outputs.

Several studies employed gamified design activities, concept cartoons, or stop-motion tools [70,77] to foster imaginative thinking and multimodal expression. In sustainability and complex systems contexts, advanced tools like systems thinking models, rich pictures, and stakeholder feedback protocols were integrated [71], offering learners authentic engagement with real-world variables.

Digital tools were used in blended settings: Moodle, Zoom, Jamboard, and Padlet featured as collaborative spaces for design communication and feedback [78,79]. Several studies also involved robotics kits, visual programming tools, and prototyping tasks to bridge physical making with algorithmic thinking [80,81].

Notably, rubric-based assessments, design showcases, and student artifacts like diagrams and models were used to evaluate DT outcomes across stages, from empathy to final implementation [82,83].

The selected studies span a wide range of science domains. General science was most common (10 studies), followed by STEM education (8), biology (6), chemistry (3), physics (3), and niche areas like earth science, microbiology, environmental science, and sustainability education. In chemistry, Ananda et al. [63] and Aris et al. [68] used DT to foster critical thinking and innovation competence, while in biology, Honra & Monterola [65] focused on academic resilience and adaptability. Sustainability was addressed through transdisciplinary design studios [71,84], while Vardakosta et al. [69] implemented DT in a university-level physics course to explore co-creation around energy solutions.

The duration of DT interventions varied considerably. Short-term formats (1–4 weeks) were common in secondary contexts [68,75], especially when DT was embedded in project cycles or workshops. Medium-duration programs (6–15 weeks) were more prevalent in higher education, allowing for deeper prototyping and iteration [66,69].

Some studies featured extended engagements: Ananda et al. [63] ran a 9-month intervention within chemistry education, and Sluijs et al. [84] described a two-year longitudinal design course incorporating systems and stakeholder engagement. However, in 11 studies, the duration of implementation was either not reported or ambiguously indicated, thereby limiting clarity regarding instructional timelines and hindering cross-study comparability.

3.2.2. Instructional contexts and methodologies

The 40 selected studies implementing DT in science education were conducted across a variety of educational levels, methodological orientations, participant groups, and geographical regions (Figure 11).

A total of 14 studies were implemented at the secondary level [63,67], and 13 at the higher education level [66,85]. DT was also applied in middle school contexts [86,87] and primary education [73,80]. One study spanned both secondary and primary levels [72], while one was situated in a pre-primary context [59] and one reported a general level of implementation [81].

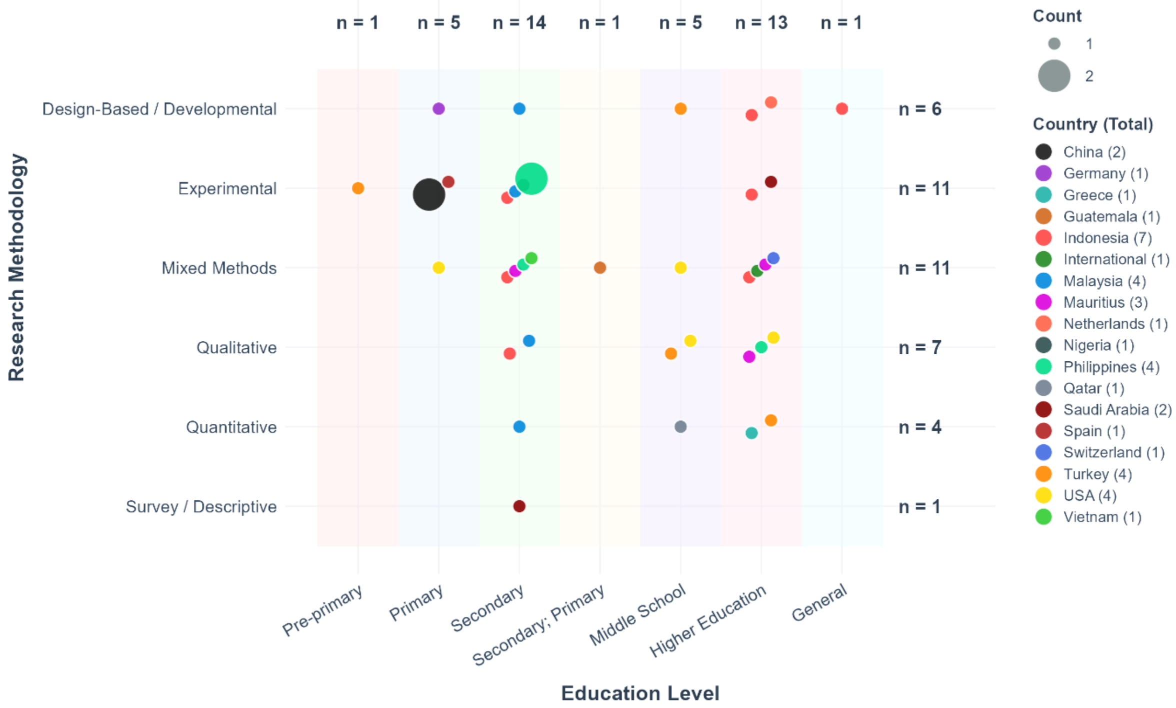

Figure 11. Distribution of studies by research methodology, education level, and country.

The studies employed a range of methodological approaches. Experimental designs were the most frequently used (n = 11) [64,75], followed by mixed methods (n = 11) [77,85]. Seven studies employed qualitative approaches [63,66], six followed a design-based or developmental methodology [68,87], four were quantitative [88,89], and one was a survey-based descriptive study [67].

School students were the most frequently involved participants (n = 17) [63,67], followed by graduate students (n = 8) [64,76]. Seven studies involved mixed participant groups including students, teachers, and/or experts [66]. Four studies specifically targeted teacher candidates [77,85]. Other sample types included teachers [71], curriculum experts [89], and preschool children [69].

The studies represented a globally diverse distribution. Indonesia had the highest representation (n = 7), followed by the United States (n = 4), Malaysia (n = 4), the Philippines (n = 4), and Turkey (n = 4). Mauritius contributed three studies, while Saudi Arabia [67,90] and China were each represented in two. Other countries represented by a single study included Qatar, Guatemala, Germany, Vietnam, Switzerland, Spain, Nigeria, the Netherlands, and Greece, and one was categorized as international [79].

3.2.3. Theoretical and pedagogical frameworks

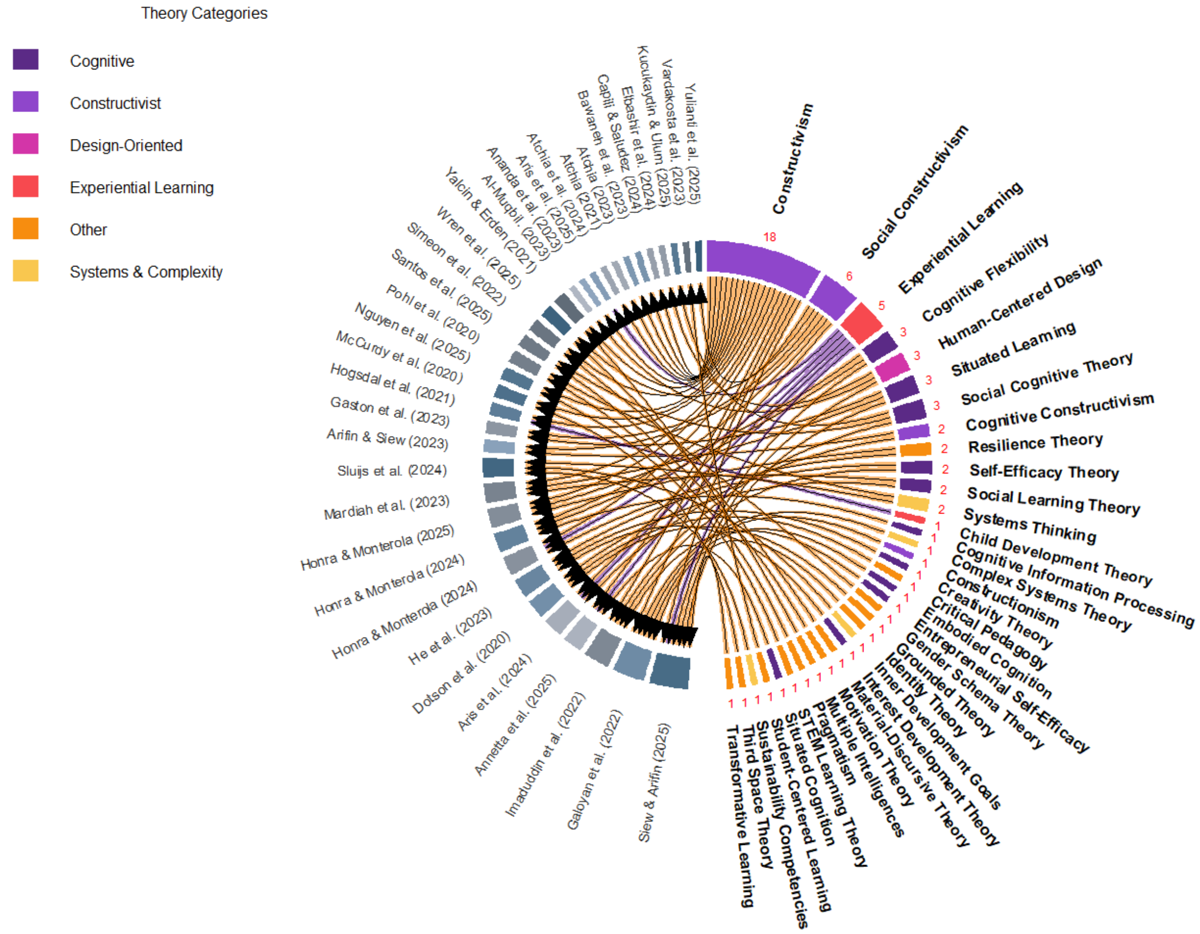

Figure 12. Network analysis of theoretical frameworks.

The analysis of the reviewed studies revealed a strong alignment with learner-centered pedagogical designs and constructivist theoretical perspectives, particularly in the integration of DT into science and STEM education. Both theoretical and pedagogical frameworks were identified and categorized, highlighting how instructional strategies were conceptually grounded across the literature (Figure 12).

Based on the reviewed studies, six major theory categories were identified, with constructivist paradigms emerging as the most dominant, cited in 26 instances across 17 studies. These included general constructivism, social constructivism, and cognitive constructivism, positioning learning as active, social, and contextualized, and underpinning DT's iterative and reflective processes [63,64,91]. Cognitive theories appeared in 12 instances, spanning situated cognition, cognitive flexibility, self-efficacy, and interest development, framing DT as a scaffolded, mentally engaging process that fosters adaptability and higher-order reasoning [65,80]. Design-oriented perspectives such as human-centered design were noted in four studies [67,92], emphasizing empathy, ideation, and prototyping, while experiential learning theories were used in five studies [66,68], aligning DT with reflective, action-based practice. Systems and complexity-oriented theories, including systems thinking, complex systems theory, and sustainability competencies, appeared in three studies [84,93], providing a macro-level lens for addressing interdependent problem spaces. Finally, diverse but less frequent frameworks such as critical pedagogy, grounded theory, identity theory, gender schema theory, and transformative learning were found in around 15 instances, highlighting socio-cultural, motivational, and emancipatory dimensions of DT in specific contexts.

Table 5. Pedagogical frameworks used in the studies.

Category	Papers	Author(s)	Frameworks
5E-based	2	Honra & Monterola[65]; McCurdy et al. [83]	PBDT (5E+DT)
Design-based	23	Arifin & Siew[64]; Aris et al. [68]; Atchia [76,85]; Atchia et al. [77]; Capili & Saludez [94]; Elbashir et al. [89]; Galoyan et al. [70]; Gaston et al. [73]; He et al. [80]; Honra & Monterola [74,91]; Nguyện et al. [82]; Pohl et al. [93]; Santos et al. [95]; Siew & Arifin [92]; Simeon et al. [61]; Sluijs et al. [84]; Vardakosta et al. [69]; Winiasri et al. [96]; Wren et al. [79]; Yalçın & Erden [59]; Çift çi & Top çu [87]	DTOBI; DTSICM; DTEL; Personalized DT; DDR/Developmental DT; STEM+Values DT; Systems+DT; Interdisciplinary DT; Challenge-based DT; Double Diamond DT; Design Thinking (General)
Experiential	2	Al-Muqbil [67]; Küçükaydın & Ulum [97]	Experiential DT
Inquiry-based	4	Annetta et al. [66]; Aris et al. [88]; Bawaneh et al. [90], Çift çi & Top çu [86]	Inquiry-DT
Other	4	Dotson et al. [72]; Högsdal et al. [98]; Rizqillah et al. [81]; Yulianti et al. [99]	Misc. Design Thinking (collaborative/peer-led)
Project-based	5	Ananda et al. [63]; Baiq [75]; Imaduddin et al. [100]; Mardiah et al. [78]; Zhu et al. [101]	STEAM-PjBL

Pedagogically, the reviewed studies displayed substantial variation, yet five dominant categories emerged: design-based, project-based, inquiry-based, experiential, and miscellaneous/uncategorized approaches (Table 5). The most prominent was design-based pedagogy, evident in 23 studies, where DT was positioned both as a structural method and as a philosophical stance for science teaching, emphasizing empathy, iteration, and solution-focused inquiry. These studies frequently employed structured models such as DTEL and DTSICM, or integrated DT into interdisciplinary STEM contexts [64,69,84]. Project-based learning (PBL) was implemented in 5 studies [63,78], most often in the form of STEAM-PjBL, engaging learners in extended, authentic design challenges guided by DT processes. Inquiry-based frameworks appeared in 4 studies [66,86], using socioscientific or problem-driven inquiry as a vehicle for DT integration. Experiential learning was applied in 2 studies [67,97], foregrounding active participation, reflection, and connections to real-world scenarios. Finally, 4 studies [72,98] employed collaborative or hybrid pedagogies where DT featured more generally without being tied to a formal instructional model.

3.2.4. Targeted competencies and learning outcomes

A comprehensive synthesis of learning outcomes across the 40 empirical studies, as shown in Figure 13, revealed that DT promotes a multifaceted set of competencies in science and STEM/STEAM education, encompassing cognitive, affective, creative, and collaborative domains

[63,68,72,89,91]. Among these, social-emotional skills emerged as the most frequently reported category, highlighted in 13 studies [90,95,97]. These included motivation, self-efficacy, academic resilience [74,91], interest development [89], science identity [70], and sustained student engagement [72,85]. Cognitive skills, cited in at least 11 studies [68,73,101], ranged from inquiry and reflective thinking [88] to subject knowledge, conceptual understanding [99], and cognitive flexibility [65]. Critical thinking, emphasized in four studies [63,96], included analytical reasoning, content critique, and independent judgment. Creative skills were showcased in five studies, such as entrepreneurial creativity [64,92], problem posing [75], and idea generation [59]. Two studies specifically reported innovation competence through iterative design and framing user-centered problems [68,88]. Problem-solving skills, including complex reasoning and real-world application, were evident in four studies [82,98], while collaborative skills such as teamwork, peer feedback, and communication emerged in three studies [78,100]. These outcomes reflect DT's capacity to enhance both academic performance and essential 21st-century skills, fostering well-rounded learners equipped to engage with real-world scientific and societal challenges. Ultimately, DT-based pedagogies advance holistic development—intellectual, emotional, and social—through experiential, student-centered approaches [70,91,95], making them particularly relevant for sustainable and transformative science education.

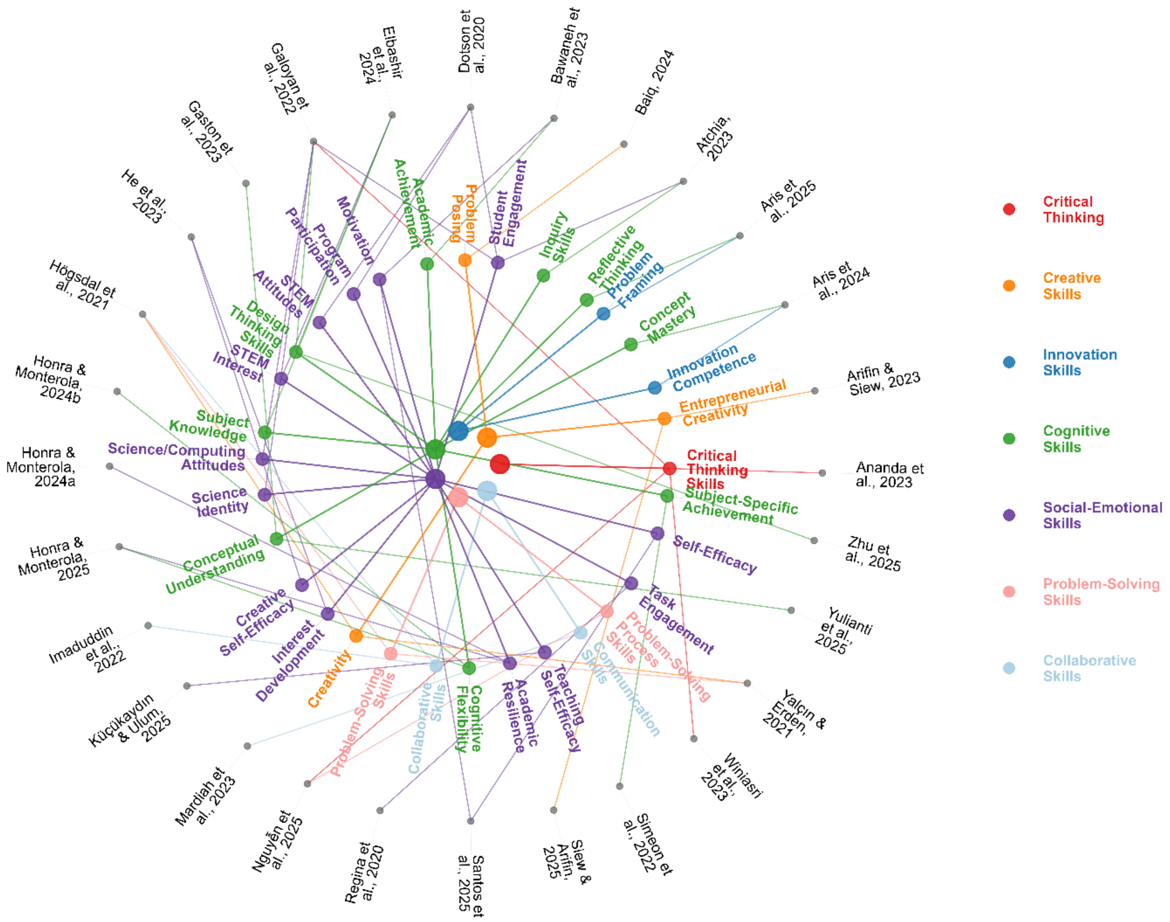

Figure 13. Keyword co-occurrence network of broader targeted competencies.

3.2.5. Barriers and catalysts in DT implementation

Implementing DT in science and STEM/STEAM education presents both challenges and enabling conditions, as evidenced in the 40 reviewed studies (Table 6). Key challenges include curriculum rigidity, time constraints, and misalignment with standardized assessment [67,93,94]. Teachers often lacked adequate training and confidence to facilitate DT, facing resistance to shifting roles from instructors to facilitators [68,87]. Students, too, struggled with abstract thinking, collaboration, and sustained engagement [63,69]. Resource limitations, especially materials and digital tools, posed further barriers [70], while group dynamics and conceptual misunderstandings hindered implementation in several contexts [66,93].

Conversely, as shown in Figure 14, several enabling factors supported DT integration. Professional development, mentorship, and scaffolded teacher support were repeatedly emphasized [66,102]. Empathy-driven learning, structured teamwork, and real-world problem contexts enhanced engagement and relevance [61,68]. Successful models leveraged established DT frameworks and iterative design processes [79,86], fostering creativity, agency, and innovation. Institutional support, value alignment, and inclusive learning environments further contributed to effective DT adoption [93,99]. Thus, DT's success hinges on both pedagogical readiness and system-level facilitation.

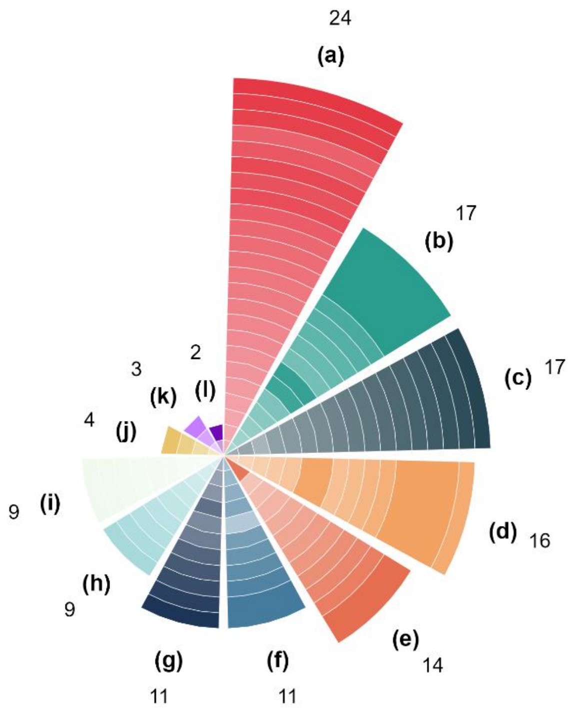

Figure 14. Enabling factors of implementing design thinking in science education.

Note: (a) Structured DT frameworks, 24; (b) empathy and human-centeredness,17; (c) real-world relevance, 17; (d) creativity and innovation, 16; (e) collaboration and teamwork, 14; (f) teacher training and facilitation, 11; (g) student engagement and agency, 11; (h) institutional support, 9; (i) cognitive competencies, 9; (j) technological tools and environments,4; (k) sustainability alignment, 3; (l) equity and inclusion, 2.

Table 6. Categorization of reported challenges in DT–based science and STEM/STEAM education studies.

Thematic category	**Challenges**	**Source(s)**
Curriculum/structural	Curriculum misalignment, time-intensive, exam-focused culture, time management challenges, curriculum rigidity, time constraints, time/content pressure, curriculum barriers, time and HR constraints, system fragmentation, scale challenges, time pressure, time scarcity, workload	Al-Muqbil [67]; Atchia [85]; Atchia et al. [77]; Capili & Saludez [94]; Çiftçi & Topçu [86]; Dotson et al. [72]; Honra & Monterola [74]; Imaduddin et al. [100]; Pohl et al. [93]; Siew & Arifin [92]; Sluijs et al. [84], Vardakosta et al. [69]
Resource/material	Lack of resources, tech access issues, rework due to tools, tech unpreparedness, limited materials, material/tool limitations, time/resource limits, technical barriers, tool issues	Al-Muqbil [67]; Annetta et al. [66]; Baiq [75]; Capili & Saludez [94]; Çiftçi & Topçu [86]; Galoyan et al. [70]; Högsdal et al. [98]; Mardiah et al. [78]; Santos et al. [95]
Teacher preparedness	Low teacher readiness, resistance to innovation, lack of teacher confidence, lack of training and DT clarity, role shift challenge, teacher–student dynamics, trainer uncertainty, teacher training, risk-averse culture, educator training limits, teacher inexperience, mentor need	Al-Muqbil [67]; Annetta et al. [66]; Aris et al. [88]; Çiftçi & Topçu [87]; He et al. [80]; Högsdal et al. [98]; Honra & Monterola [74,91]; Küçükaydın & Ulum [97]; Sluijs et al. [84]
Student-cognitive	Difficulty with critical thinking, difficulty with prototyping, failed prototyping, problem formulation difficulty, digital distraction, math gaps, high cognitive load, student hesitation, student resilience gaps, motivation decline, idea generation difficulty, passivity, insecurity, student persistence, novel shape design, spatial immaturity	Ananda et al. [63]; Atchia [85]; Baiq [75]; Capili & Saludez [94]; Dotson et al. [72]; He et al. [80]; Högsdal et al. [98]; Honra & Monterola [91]; Küçükaydın & Ulum [97]; Santos et al. [95]; Siew & Arifin [92]; Vardakosta et al. [69]; Zhu et al. [101]
Conceptual/contextual	Narrow CT interpretation, conceptual DT stage difficulty, DT ambiguity, STEAM–DT complexity, stakeholder demands, stage continuity problems, empathy–test gap, technocratic bias, empathy sidelined, dominant narratives, contextual understanding demands, linear DT risk, abstract concept difficulty, limited DT application	Annetta et al. [66]; Çiftçi & Topçu [87]; Honra & Monterola [91]; Mardiah et al. [78]; Nguyễn et al. [82]; McCurdy et al. [83]; Siew & Arifin [92]; Sluijs et al. [84]; Yulianti et al. [99]
Group/collaboration	Uneven group roles, poor communication, stakeholder tension, stakeholder logistics, group size issues	Çiftçi & Topçu [86]; Pohl et al. [93]; Sluijs et al. [84]; Vardakosta et al. [69]
Assessment	Assessment mismatch, risk of shallow task focus	Gaston et al. [73]

3.2.6. Limitations and future directions

The reviewed studies collectively revealed a range of methodological, contextual, and pedagogical limitations that constrain the generalizability and long-term impact of DT in science and STEM/STEAM education. One of the most frequently cited limitations was the limited generalizability of findings, primarily due to small, homogeneous, or purposively selected samples [67,70]. Many studies were restricted to short-term interventions, limiting the ability to evaluate sustained learning outcomes, iteration cycles, and behavioral shifts [80,95]. Several studies used non-randomized or cross-sectional designs without control groups, thereby limiting causal inference [89,91]. A number of works relied heavily on self-reported data or single methods, risking bias and reducing the depth of insight into student learning processes and teacher practices [85,97]. Instrumentation concerns, such as low reliability scores and lack of psychometric validation, further weakened the methodological robustness of several studies [73]. Additionally, DT-specific constraints, such as limited iteration, poor sketching skills, and weak prototyping, were reported, especially in early and primary education settings [75,101].

The research gaps identified across these studies underscore the need for more robust theoretical integration and empirical expansion. Many studies highlighted the lack of DT research in early education and underexplored subject areas like chemistry, biology, and preschool STEM [59,80]. A notable gap is the absence of structured pedagogical frameworks and validated models for DT implementation in science classrooms [76,94]. DT's intersection with competencies such as creativity, empathy, and critical thinking is often underexamined or narrowly framed, with limited exploration of how these evolve through the DT process [73,83]. Context-specific challenges, such as under-resourced schools, traditional instructional norms, and cultural constraints, were also inadequately addressed, particularly in studies from Southeast Asia and Africa [61,78]. Furthermore, the integration of DT with transdisciplinary themes like sustainability, social justice, or entrepreneurship remains a significant blind spot in the literature [74,84].

Looking ahead, authors across studies propose future directions that are both ambitious and pragmatic. A majority call for expansion of DT application across subjects, age levels, and contexts, with a focus on scaling interventions to larger and more diverse populations [67,96]. Methodological improvements are strongly emphasized, including the adoption of longitudinal designs, randomized trials, and mixed-method approaches to evaluate deeper learning impacts and systemic changes [80,91]. There is also a strong call to develop structured DT-based instructional models, teacher training modules, and integrated curricula that promote critical 21st-century skills such as creativity, empathy, and sustainability leadership [73,97]. Several studies encourage investigating the role of digital technologies, such as AI and AR, in enhancing DT environments and facilitating collaborative learning [94]. Other suggested directions include integrating culturally responsive content, involving stakeholder co-design, and exploring interdisciplinary collaborations that bridge science with engineering, business, and the arts [79,92]. Overall, the future of DT research in science education hinges on inclusive, theoretically grounded, and context-sensitive pedagogies that prepare learners for real-world complexity.

3.3. Proposed pedagogical framework: The ECLIPSE-DT model

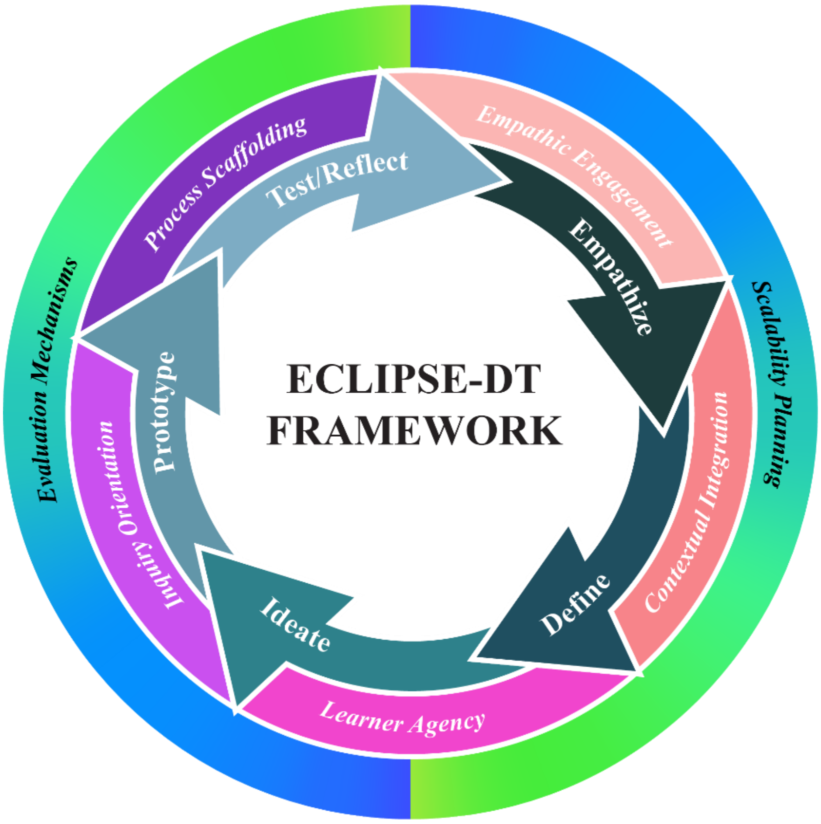

Figure 15. ECLIPSE-DT framework for design thinking in science and integrated STEM/STEAM education.

To address persistent gaps in the implementation, assessment, and pedagogical coherence of DT within science and integrated STEM education, this study introduces the ECLIPSE-DT Framework (Figure 15), a comprehensive conceptual model rooted in constructivist, experiential, and design-based learning theories (Dewey, 1938; Kolb, 1984; Vygotsky, 1978). Developed through a synthesis of 40 empirical studies, the framework bridges theoretical ideals with classroom realities, offering a pragmatic and research-driven structure for DT integration.

The framework employs the EDIPT cycle—empathize, define, ideate prototype, and test/reflect—adapted from the Stanford d.school model and validated across multiple instructional contexts. Surrounding this iterative process are seven interconnected components represented by the acronym ECLIPSE, encompassing five pedagogical principles and two implementation strategies. Each element corresponds directly to key challenges in the literature.

Empathic engagement centers the design process around users and real-world contexts, cultivating moral reasoning, motivation, and emotional connection. This addresses the often-overlooked gap in DT fidelity, where critical phases like empathy and reflection are underutilized [84,85]. By embedding user-centered learning as a foundation, this component strengthens holistic engagement with both social and scientific dimensions.

Contextual integration ensures that learning is grounded in authentic scientific and societal challenges. When DT is applied to real-world issues, such as environmental systems or public health, it enhances relevance and application [70,93]. This responds to the institutional and curricular constraints gap, allowing DT to be flexibly adapted to varied content and educational settings.

Learner agency promotes student-driven inquiry, collaboration, and metacognition, thereby addressing the gap in professional development and teacher-centric implementation. As shown in studies like Nichols et al. [103], fostering agency among students also models how DT can be transferred to teacher education and reflective practice.

Inquiry orientation aligns DT tasks with disciplinary scientific processes, ensuring creativity is balanced by content accuracy and rigor. This component directly addresses the gap in disciplinary depth, particularly where DT is applied narrowly in biology or chemistry, and not extended into Earth science, environmental studies, or physics [61,99].

Process scaffolding provides structured supports, such as empathy maps, ideation canvases, and stepwise guides, that help students and teachers navigate complex DT cycles. It addresses both the gap in teacher preparedness and the cognitive overload experienced by novice learners [101,104]. Scaffolding thus becomes a cornerstone for inclusive and equitable DT integration.

The outer layer of the framework includes two critical implementation strategies. *Scalability planning* supports the expansion of DT beyond pilot projects, offering pathways for integration into system-wide curricula, cross-disciplinary programs, and various institutional formats. This directly tackles the gap in scalability and generalizability of DT interventions [65,105].

Evaluation mechanisms respond to the gap in assessment practices, especially the lack of tools for capturing process-oriented competencies such as iteration, empathy, and problem-solving [63,69]. Through the use of rubrics, reflection logs, and portfolio-based assessments, this component ensures that DT learning outcomes are documented and valued appropriately.

The ECLIPSE-DT Framework is purposefully adaptable across educational levels and cultural settings. In primary classrooms, young learners might redesign their schoolbags to make them eco-friendlier and more user-friendly, introducing empathy and prototyping in playful ways. At the secondary level, students could develop low-cost solutions for local issues, like filtering drinking water in rural areas, linking scientific inquiry with social relevance. In teacher education, pre-service teachers can co-create interdisciplinary modules, blending DT with sustainability and equity goals. Culturally, the framework embraces collectivist values through community-centered projects, such as designing dengue-prevention campaigns in Southeast Asia, while also supporting individual innovation, like digital health apps in Western contexts. Whether using paper sketches in resource-limited schools or interactive whiteboards in high-tech labs, the framework ensures DT remains accessible, scalable, and meaningful across global science and STEM education landscapes.

The ECLIPSE-DT Framework functions as an instructional guide and a strategic response to the systemic, curricular, and pedagogical challenges facing the integration of DT in science education. The model enables sustainable, scalable, and meaningful engagement with DT across educational levels and learning environments by synthesizing theory, empirical insights, and implementation strategy.

4. Discussion

This study offers a dual-layered synthesis, through a bibliometric and systematic literature review, on using DT in science and integrated STEM/STEAM. The findings validate the increasing scholarly attention to DT and clarify how it is pedagogically implemented across educational levels, disciplines, and geographic contexts.

The steady rise in publications since 2018, peaking in 2024, underscores a growing global interest in DT as a transformative pedagogical approach in science and STEM education [24,32,106]. This trend reflects a broader educational shift toward learner-centered, inquiry-driven, and innovation-based instruction that targets 21st-century competencies [107]. Notably, the citation peak in 2015 is attributed to a single yet highly influential paper by English and King [108], which explored STEM learning through engineering design in fourth-grade aerospace investigations. Despite being the only publication that year, its substantial citation count suggests it served as a seminal work that catalyzed subsequent research interest in DT applications within K–12 science education. Similarly, the study by Kuo et al. [52], integrating DT through project-based learning in a human-computer interaction course, represents another landmark in terms of scholarly influence and practical implementation in higher education contexts. Meanwhile, lower citation averages in recent years are expected due to citation lag [109], not necessarily reflective of research quality. These patterns affirm DT's growing academic legitimacy and its alignment with constructivist and competency-based educational paradigms [13,110]

Authorship and institutional analyses further validate the field's maturing scholarship. Prolific contributors such as Ladachart L. and institutions like Purdue University and Universiti Teknologi Malaysia signify both sustained engagement and institutional investment in DT-integrated STEM pedagogy. Interestingly, authors with fewer publications but high citation counts, such as English L. D. and King D. T., demonstrate that impactful, well-cited studies are shaping the field's intellectual trajectory, reflecting the value of quality alongside productivity [109].

At the national level, the United States, China, and Australia emerged as central contributors, consistent with their broader leadership in educational research infrastructure and innovation [111]. However, regional disparities are evident: Malaysia, for instance, showed high publication output but relatively low citation impact, pointing to differences in visibility, dissemination, and research reach [14,38,112]. The global distribution, spanning Southeast Asia, Europe, North America, and Africa, reflects both the diversity and unevenness of scholarly ecosystems, influenced by language, funding access, and institutional networks [112].

The prominence of journals such as the *International Journal of Technology and Design Education* and *Thinking Skills and Creativity* reinforces DT's positioning at the nexus of creativity, design-based learning, and STEM integration [6,13]. High m-index values and citation rates in select journals affirm scholarly recognition of DT's educational potential. Influential publications like English and King [108] and Kuo et al. [57] have significantly advanced practical applications of DT across K–12 and higher education contexts, validating its relevance across educational levels and subject domains.

The keyword co-occurrence network reflects the thematic breadth and conceptual coherence of DT research. Keywords like creativity, project-based learning, empathy, and computational thinking signal DT's integration into both content- and competency-oriented pedagogies. The emergence of emotionally grounded terms such as empathy, innovation, and creative confidence highlights DT's shift toward human-centered, socially responsive teaching models [110,113]. These patterns affirm DT's multidimensional role, not just as a problem-solving tool but as an evolving educational paradigm bridging cognitive, affective, and collaborative dimensions.

Finally, collaboration patterns reveal a field characterized by both scholarly cohesion and expanding diversity. At the country level, strong bilateral ties, like US–Canada and China–Hong Kong, underscore established research alliances, while emerging Southeast Asian players (e.g., Indonesia, Malaysia) demonstrate growing regional engagement in the post-2020 period [114,115].

Author-level networks reveal a balance between long-standing academic dyads (e.g., Avsec–Savec; Kijima–Yang-Yoshihara) and newer partnerships, suggesting both continuity and renewal in DT research ecosystems. Dense internal linkages within clusters reflect trust, mutual vision, and thematic synergy, essential for advancing complex, interdisciplinary educational innovations like DT.

The analysis of 40 empirical studies confirms that DT is most effectively implemented when grounded in structured frameworks and adapted to local instructional needs. The dominance of the Stanford d.school model reflects its alignment with inquiry-oriented science education, yet frequent adaptations underscore DT's contextual flexibility and its responsiveness to learner needs [116,117]. The emergence of alternative and hybrid models, such as those integrating systems thinking or human-centered design, indicates a pedagogical shift toward transdisciplinarity and authentic problem-solving in science contexts [71,84].

The broad application of DT across educational levels supports prior findings that DT is developmentally scalable but requires differentiated scaffolding [118]. The concentration of studies in secondary and higher education suggests that these settings offer greater curricular flexibility and learner readiness for complex design processes [119]. The prevalence of experimental and mixed method designs indicates an evolving commitment to both measuring impact and understanding learning processes, addressing earlier critiques of DT research as being too anecdotal or design-centric [120].

The consistent alignment of DT with constructivist and experiential learning theories affirms its theoretical compatibility with science education reform, especially in fostering active, student-centered engagement [15]. However, the absence of clear theoretical articulation in many studies reflects a persisting conceptual gap that weakens pedagogical coherence and limits replication [117].

The learning outcomes identified—spanning social-emotional skills, cognitive competencies, creativity, and inquiry—align with global calls for education that supports 21st-century competencies and sustainability literacies [121]. Yet, underreporting of collaboration and innovation competence suggests that some studies fail to operationalize DT's full potential [118].

Challenges such as curriculum rigidity, lack of teacher readiness, and assessment misalignment are consistent with structural barriers previously reported in DT adoption [116]. Conversely, enabling conditions, professional development, institutional support, and real-world relevance mirror success factors in related design-based pedagogies [119,122].

To advance the field, future research must adopt theoretically grounded, methodologically robust designs and explore DT's intersection with themes like sustainability, equity, and interdisciplinarity [84,121].

5. Conclusions

5.1. Summary and discussion of main findings

This study presents a dual-layered synthesis, through bibliometric analysis and an SLR, of the role of DT in science and integrated STEM/STEAM education from 2011 to 2024. The bibliometric results confirm a growing scholarly interest in DT, particularly from 2018 onward, with 2024 marking the highest annual publication count. This upward trend reflects a global educational shift toward learner-centered, inquiry-based, and innovation-driven pedagogies that prioritize 21st-century competencies [13,107]. Seminal works such as English and King [108] and Kuo et al. [57] catalyzed this shift, gaining high citations and validating DT's educational relevance across primary and tertiary science education.

Authorship and institutional trends show a maturing research field. While prolific contributors such as Ladachart L. and institutions like Purdue University illustrate sustained scholarly engagement, highly cited yet infrequent contributors demonstrate that quality and theoretical influence matter as much as volume. Nationally, the United States, China, and Australia dominate both publication and citation impact, although disparities persist; for instance, Malaysia and Indonesia have high output but lower citation reach, indicating uneven visibility and dissemination.

Keyword co-occurrence and cluster analyses reinforce the thematic breadth of DT research, highlighting dominant concepts such as creativity, empathy, computational thinking, and project-based learning. The evolution of emotionally grounded and human-centered terms like empathy, innovation, and creative confidence suggests that DT has shifted from a procedural tool to a holistic educational paradigm connecting cognitive, affective, and collaborative domains [11,110]. Collaboration networks across countries and authors reveal both strong academic dyads and emerging regional partnerships, especially in Southeast Asia and Europe, reflecting both intellectual continuity and expansion [115].

The SLR component adds depth to these bibliometric patterns, revealing that DT is most commonly implemented using the Stanford d.school model. However, this model is frequently adapted, expanded, hybridized, or localized to better align with learner needs, content specificity, or institutional constraints. DT has been applied across a broad range of subjects, especially general science, biology, chemistry, and sustainability, with varying durations and tools, including empathy interviews, reflective journals, prototyping worksheets, and digital collaboration platforms. These instructional strategies promote student agency, problem-solving, and metacognitive reflection.

Theoretical grounding remains uneven: while many studies align with constructivist, experiential, and design-based learning paradigms, over half do not explicitly articulate a guiding theory. This conceptual gap undermines coherence and limits the replicability of DT-based interventions [117]. Despite this, DT consistently demonstrates alignment with frameworks that emphasize inquiry, creativity, and learner agency, features that make it particularly suitable for science education reform.

Learning outcomes clustered around cognitive, creative, and socio-emotional domains, with competencies such as self-efficacy, critical thinking, science identity, and resilience being frequently reported. However, collaborative skills and innovation competence were less emphasized, indicating partial implementation of DT’s full potential. This gap may be tied to challenges in assessment practices, time constraints, or teacher preparedness.

To bridge these gaps, the study proposed the ECLIPSE-DT Framework, synthesizing empirical insights and theoretical foundations into a coherent pedagogical model. It incorporates seven elements—empathic engagement, contextual integration, learner agency, inquiry orientation, process scaffolding, scalability planning, and evaluation mechanisms—which directly address known implementation barriers such as lack of assessment tools, misalignment with curricula, and teacher role ambiguity. In doing so, it offers a scalable, theory-informed, and context-sensitive structure to guide DT integration in diverse science education settings.

In summary, the findings affirm DT’s transformative potential when supported by coherent frameworks, appropriate scaffolding, and institutional support. However, its successful and sustained integration depends on overcoming conceptual ambiguity, expanding application into underrepresented subjects and levels, and embedding DT within broader educational goals such as sustainability, equity, and interdisciplinary problem-solving.

5.2. Implications

The introduction of the ECLIPSE-DT Framework marks a significant pedagogical innovation with wide-reaching implications for curriculum design, teacher education, and educational policy. By systematizing DT around seven core principles and strategies, the framework provides educators with a clear blueprint for aligning creativity with content rigor, empathy with inquiry, and student agency with instructional structure.

For curriculum developers, ECLIPSE-DT facilitates the contextualization of science education through real-world problem solving, allowing DT to be embedded across disciplines, including underutilized areas like physics, Earth science, and sustainability. Policymakers can draw on this model to design scalable programs that move beyond pilot interventions toward institutional integration, thereby addressing SDG-aligned goals such as creativity, resilience, and global citizenship.

In teacher education, the framework's focus on process scaffolding and empathic engagement offers a replicable approach to professional development that builds both the technical and emotional competencies required to facilitate DT. Through evaluation mechanisms, such as process rubrics, reflective portfolios, and iteration logs, it also establishes a foundation for assessing competencies traditionally overlooked in standardized assessments, such as empathy, resilience, and iterative thinking.

Furthermore, the scalability planning component enables education systems to expand DT pedagogies across school levels, formats, and geographies. By grounding DT in authentic scientific and societal contexts, the framework supports learner-centered pedagogies that are not only innovative but also sustainable and culturally responsive. It holds particular value in equipping students and teachers to navigate complex, interdisciplinary challenges through design-oriented problem-solving.

5.3. Limitations

While this study provides robust conceptual and empirical insights, several limitations should be acknowledged. First, the bibliometric component relied solely on Scopus data, which may exclude relevant studies indexed in other databases or published in non-English or regional journals. Although the SLR synthesized 40 studies across a range of contexts, it remains limited in scope relative to the global research landscape. Some included studies lacked transparency in theoretical framing, implementation duration, or assessment detail, which may affect synthesis reliability.

The ECLIPSE-DT framework, while grounded in theory and derived from empirical patterns, remains a proposed model requiring further field validation. Its components, though conceptually rigorous, need to be tested across diverse education systems, subject areas, and student populations to determine scalability, cultural adaptability, and long-term impact. Additionally, most studies reviewed focused on short-term interventions; thus, questions remain about how DT competencies evolve over extended timelines or through iterative refinement.

Future research should empirically validate the ECLIPSE-DT model through mixed-methods studies, longitudinal interventions, and cross-cultural replications. Particular attention should be paid to refining assessment strategies for non-cognitive competencies and exploring DT's integration with themes like sustainability, ethics, and justice. Only through continued empirical grounding and iterative model refinement can DT pedagogy fulfil its transformative potential in science education.

Author contributions

Conceptualization, Mary Vineetha Thomas and Ashish Saseendran; Methodology, Ashish Saseendran and Mary Vineetha Thomas; Formal analysis, Ashish Saseendran; Investigation, Ashish Saseendran; Data Curation, Ashish Saseendran; Writing—Original Draft Preparation, Ashish Saseendran; Writing—Review and Editing, Mary Vineetha Thomas and Ashish Saseendran; Supervision, Mary Vineetha Thomas.

Use of Generative AI tools declaration

The authors confirm that no generative AI tools were used to prepare, write, or edit this manuscript. All content is entirely original and the result of the authors' own work and intellectual effort.

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Conflict of interest

The authors declare no conflict of interest in this paper.

Ethics declaration

The author declared that no ethics approval is required for the study.

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