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Instructional Design in Science Education: A Bibliometric Analysis of Trends and Applications

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Abstract: Instructional design, grounded in learning theory, is a systematic approach aimed at enhancing teaching quality, and it holds significant importance, particularly in the rapidly evolving field of education. Understanding past and future trends in instructional design within science education is crucial for a comprehensive grasp of this area and its future prospects. This research utilizes bibliometric analysis on 1,148 journal articles extracted from the Web of Science database to examine the trends and applications of instructional design within science education. Key findings include three major clusters from co-citation analysis: "Theoretical Frameworks and Methodologies," "Cognitive Load Theory and Instructional Design," and "Instructional Design in Multimedia and Complex Environments." Additionally, co-word analysis highlights emerging themes such as computational thinking and active learning in STEM education. This study offers a comprehensive perspective on instructional design in science education, providing valuable guidance for stakeholders to improve teaching practices and educational outcomes.

Keywords: Bibliometric analysis, Educational research, Instructional design, Science education, Web of Science

1. Introduction

Instructional design (ID) is defined as a systematic process aimed at creating more effective and efficient learning experiences (Gavin, 2024; Rhodes et al., 2024; Thohir et al., 2021). This approach simplifies learning activities by leveraging our understanding of information technology, learning theories, educational research, systematic analysis, and management methods (Melo & Baruque, 2011; Ngussa, 2014). Instructional designers are identified as experts who possess extensive knowledge in learning theories, instructional design (ID) theories, and ID models, while staying updated with technological advancements (Chartier, 2021). They exhibit core skills such as analysis, design and solution generation, problem identification, and project management, along with dispositions like flexibility, adaptability, openness , and intentionality (Chartier, 2021).

Over the last five decades, there has been a consistent rise in the number of instructional designers employed in non-academic environments (Wheeler, 2022). This shift has primarily involved practitioners alongside scholars, fostering greater collaboration between the two groups and contributing to the broader development and application of ID. Bodily et al. (2019) observed that instructional design scholarship spanned multiple disciplines, including instructional systems, educational technology, curriculum development, learning sciences, and psychology. As educational practices have advanced, integrating experiential ideas and theories, the instructional design field has likewise evolved (Pauls, 2023). Thus, it is vital to conduct a rigorous and systematic analysis to understand the past and future trends in ID. ID is recognized as a specialized practice, enabling educators to determine the optimal approaches to achieving specific learning goals. Furthermore, it is acknowledged as a discipline that contributes to the broader knowledge base by determining optimal learning environments for specific populations and objectives (Reigeluth, 1983a). Moving forward, it is essential to consider how instructional design principles are applied to specific topics, such as science, to provide insights into how these principles influence scientific education and research methodologies.

According to Dewey (1923), science is defined as "grounded knowledge" (p. 380). Further, science, as characterized by the systematic study of natural phenomena, has evolved from ancient practices to modern disciplines. This evolution has continuously expanded our understanding of the world through rigorous research and experimentation (Dictionary, 2023). The significance of science for our society and world is undeniable (Bradley, 2005). Numerous publications underscore science's critical role in sustaining the economic prosperity of modern societies (Stuckey et al., 2013). This importance justifies the necessity of science education for future sustainable development (Burmeister et al., 2012) and for enabling proactive involvement in social matters (Roth & Lee, 2004). Siegel (1989) emphasized that science education could and should become a core component of education. Stuckey et al. (2013) emphasize that pertinence in science education encompasses a broad spectrum, extending beyond traditional subjects to include STEM education and interdisciplinary studies. In conducting research on the background of science education, it is vital not to focus solely on the traditional core subjects of biology, physics, and chemistry. Instead, the scope should encompass broader aspects of science education, including STEM education (Li et al., 2020; Martín-Páez et al., 2019; Tytler, 2020) and interdisciplinary scientific studies (Mazzocchi, 2019; Raimbault, 2019; Wagner et al., 2011). Therefore, it is essential to systematically understand and grasp the past and future trends of instructional design in science education to promote in-depth research and innovative development in this field (Eymur & Çetin, 2024; Jia et al., 2024; Zou et al., 2022). This comprehensive understanding will enable the advancement of educational practices and aid in the ongoing evolution of scientific education and research methodologies.

As a method grounded in quantitative data and analysis, bibliometric analysis provides a structured approach for assessing the academic landscape within the domains of science and science education (AlRyalat et al., 2019). By leveraging WoS databases alongside analytical techniques like co-word and co-citation analysis, one can explore the connections among scientific publications and discern trends and patterns within the instructional design field (Donthu et al., 2021). These findings enable policymakers, industry professionals , and researchers to gain a deeper understanding of development trajectories, knowledge dissemination processes, and potential research gaps in instructional design, specifically within the realms of science, science education, and educational research (Donthu et al., 2021). With the rapid advancements in technology, the paradigms in the fields of science and education are undergoing significant transformations (Saçak et al., 2022b). Analyzing historical and emerging trends in instructional design within science education and research provides valuable guidance for shaping future research trajectories and supports informed decision-making across multiple fields, such as science education, educational research, and interdisciplinary applications (Dawson, 2022).

This research aims to provide a thorough bibliometric analysis of instructional design in the scientific domain, revealing its current status and future prospects (Saçak et al., 2022a; Wasson & Kirschner, 2020). The findings from this analysis will offer key observations for stakeholders and guide future research efforts.

1.1 Literature Review

The origins of ID can be traced to the early 20th century, starting with the school museum initiative and the visual and audiovisual teaching movement (Reiser, 2001). During the mid-20th century, incorporating media into teaching and the development of systematic instructional design processes emerged as pivotal aspects of the field. In 1965, Gagné introduced *The Conditions of Learning* (Gagné,1965), which categorized learning domains, outlined different levels of learning achievements, and detailed nine instructional events. This publication played a key role in establishing ID as a unique discipline and laid the groundwork for systematic instructional design processes (Curry et al., 2021). Amid continuous technological progress, the significance of instructional design in education has continued to grow, fostering the creation of various models aimed at enhancing teaching practices (Pauls, 2023).

ID has developed various dimensions due to advancements in instructional technologies and has been characterized in various forms (Göksu et al., 2017). Seels and Richey (2012) described it as the evaluation of processes and resources to facilitate learning. Van Harmelen (2008) emphasized the impact of learning and motivation theories on ID. Reigeluth (1983b) identified three components: methods, conditions, and outcomes. Gagne et al. (2005) included needs analysis, objectives, and environmental factors. Gustafson (1991) categorized ID models into class, product, and system types. Merging these perspectives, ID can be seen as a systematic approach encompassing analysis, design, development, evaluation, and management, grounded in learning theories to enhance teaching quality (E et al., 2005; Posner & Rudnitsky, 1994; Zhang & Sweller, 2024).

Traditional instructional design models, rooted in behaviorism, have evolved with advancements in instructional technologies, highlighting their limitations and leading to more learner-centered approaches influenced by constructivism (Fauser et al., 2006). Consequently, most ID models seek to clarify the fundamental components of a learning environment, with different models potentially better suited to various disciplines due to the unique characteristics of each field (Häkkinen, 2002; Wheeler, 2022). ID indeed varies across different disciplines, including science, due to the unique focus and requirements of each field. Research in discipline-based education highlights that instructional approaches need to be tailored to the specific content and learning objectives of each discipline to be effective. For example, in science education, discipline-based education research has shown that interactive and student-centered instructional strategies significantly enhance learning outcomes in fields like physics, chemistry, and biology. This includes methods such as interactive lecture demonstrations, which involve predicting and observing physical phenomena, and Just-in-Time Teaching, which adapts lectures based on pre-class student input (Council, Education, Education, & Research, 2012). Furthermore, a comprehensive review on the roles of instructional designers in higher education suggests that these professionals often adapt their approaches to address the particular requirements of their discipline (Pollard & Kumar, 2022). For instance, IDs in science education may focus more on developing materials that facilitate experimental and hands-on learning, while those in humanities might emphasize critical thinking and discussion-based approaches (Campbell et al., 2009; Pollard & Kumar, 2022). In summary, instructional design must be context-specific, considering the unique goals and challenges of each discipline to enhance learning outcomes. This underscores the significance of customized instructional strategies in fields like science, where empirical and practical learning experiences are crucial (Eymur & Çetin, 2024).

Instructional design broadly focuses on identifying the most effective methods or strategies to enhance learning under specific conditions. Designers frequently integrate various learning strategies into comprehensive frameworks, commonly known as instructional design models (Reigeluth, 1983a). Therefore, a systematic and comprehensive elucidation of ID or instructional design models holds significant value. Conducting a review study in a specific field aids in summarizing and synthesizing existing research, identifying research gaps, and offering suggestions for future studies (Cronin et al., 2008). For example, Ozcinar (2009) investigated the research trends in ID from 1980 to 2008 in professional journals, revealing that cognitive load theory and worked examples are among the most commonly utilized terms in the field. Cook et al. (2013) conducted a comprehensive review and meta-analysis to assess the effectiveness of various instructional design features in simulation-based education, finding significant variations in effectiveness among different features. Göksu et al. (2017) conducted a trend analysis of 113 instructional design model papers published between 1999 and 2014 in 44 international journals, finding that 23 models are prevalent, with ARCS, ADDIE, and Dick and Carey being the most frequent. Chan et al. (2021) conducted a systematic literature review on virtual chemical laboratories, analyzing research, technologies, and instructional design, and identified key trends and technological advancements in enhancing chemical education. More recently, Wheeler (2022) analyzed instructional design journal articles from 2001 to 2020 across Google Scholar, Scopus, and Web of Science, noting the United States as the most active country and a shift from instructional design technology to remote learning platforms. She suggested future research should target specific topics to gauge their impact.

These review studies highlight trends and hot topics in instructional design, offering a theoretical foundation for further studies. However, they primarily focus on specific time periods and models, lacking a comprehensive analysis of instructional design in the context of science education and science. This gap indicates the need for a broader examination of how instructional design principles are applied across various scientific disciplines, considering the unique characteristics and demands of each field. Addressing this gap could lead to more effective and context-specific instructional design practices in science education.

1.2 Present Study

To bridge this research gap, this study aims to conduct a comprehensive bibliometric analysis to explore the trends in instructional design within the contexts of science and science education. This analysis will uncover the present state and future outlook of instructional design in these fields, providing valuable insights for stakeholders and guiding future research efforts. From this bibliometric analysis, the study's objectives include the following:

1. To evaluate the most influential past research through co-citation analysis, thereby identifying the core themes and theoretical foundations of instructional design research within the domain of science education.
2. To identify key themes and research hotspots in instructional design within science education through co-word analysis, and further analyze the evolution and development trends of these research areas.

2. Methodology

2.1 Bibliometric Approach

Bibliometric research employs quantitative methods, utilizing mathematical and statistical techniques to examine the bibliographic characteristics of scientific literature. It assesses the impact of scholarly works by analyzing citations, publications, and collaboration patterns (Pritchard, 1969; Shi et al., 2022). It effectively reveals trends, structures, and dynamics within research fields (Zou et al., 2022). Through bibliometric analysis, researchers can systematically understand and grasp the overall status of a specific field, thereby promoting in-depth research and innovative development in that field (Ellili, 2024). This study employs bibliometric analysis to visualize research characteristics, trends, and contributors across subject domains, keywords, and themes, utilizing co-citation and co-word analysis to identify growth areas and future directions. Additionally, bibliographic coupling analysis is used to assess contributions from countries, authors, and sources (Khanra et al., 2022; Trinidad et al., 2021).

Co-citation analysis is a method for scientific mapping that identifies thematically similar publications by examining how frequently they are cited together (Verma & Gustafsson, 2020). This method reveals the conceptual framework of a research area and identifies thematic clusters derived from referenced works, though it primarily focuses on highly-cited works, potentially excluding recent or niche studies (Donthu, Kumar, Mukherjee, et al., 2021). Additionally, co-word analysis focuses on the actual content of publications by examining "words" extracted from author keywords, article titles, abstracts, and complete texts, unlike co-citation analysis, which focus on cited or citing publications (Wider et al., 2023). Co-word analysis is effective for enriching interpretations of co-citation (past) and bibliographic coupling (present), while also predicting future research trends (Donthu et al., 2021).

2.2 Research Design and Data Collection Procedure

The data for this study were sourced from the Web of Science (WoS) database, selected for its high quality and comprehensive coverage (Martı́n-Martı́n et al., 2021). WoS is a globally recognized research publication and citation database widely used in bibliometric studies (Yan & Zhiping, 2023).

The search strategy encompassed all relevant literature published from 1900 to August 2, 2024. The search fields were limited to topic fields, including titles, abstracts, and keywords. The keywords used in this study were: ("instructional design" OR "instructional design model" OR "learning design" OR "teaching design") AND ("science" OR "science education" OR "educational research"). To ensure comprehensive literature retrieval, "learning design" (Wheeler, 2022) and "teaching design" (Ozcinar, 2009) were included as synonyms for ID-related bibliometric keyword analysis. Additionally, to cover the broader context of "science education," the Boolean operators "AND" and "OR" were used with "science," "science education," and "educational research" to maximize the retrieval of relevant literature (Harary & Wilcox, 1967). This strategy aims to ensure a thorough and in-depth bibliometric analysis of the field of science education. The analysis covered all document types and was restricted to English-language articles. Table 1 outlines the detailed parameters employed in the search and screening process.

Prior to analysis, data cleaning was conducted to ensure accuracy by removing duplicates and correcting formatting and spelling errors (Donthu et al., 2021). The collected data were analyzed using VOSviewer version 1.6.20, which is a tool for visualizing bibliometric mapping (Mishra et al., 2024). The analysis employed co-citation analysis and co-word analysis to identify development trends and primary research directions in instructional design within the fields of science and science education.

Table 1. Search parameters

WoS Database	ALL
Time Period	1900 to August 2, 2024
Search Field	TOPIC
Search Keywords	(“instructional design” OR “instructional design model” OR “learning design” OR “teaching design”) AND (“science” OR “science education” OR “educational research”)
Citation Topics Meso	ALL
Document Type	ALL
Languages	English

3. Result and Discussion

3.1 Publication Trends and Descriptive Insights

Drawing from the search outcomes of the WoS database, the selected 1,148 articles have accumulated a total of 24,498 citations, averaging 21.34 citations per article and achieving an H-index of 72. These publications highlight the growing attention and importance of ID research in the field of science education. Although the first related publication appeared as early as 1991, significant contributions began to emerge around 2005. Following that period, publication numbers have shown consistent growth, reaching their highest point in 2021, although there was a minor decrease in 2023.

The majority of publications are concentrated within the domain of education and educational research, accounting for 53.48% (614 articles), followed by science discipline education at 21.78% (250 articles) and computer science interdisciplinary applications at 11.93% (137 articles). This distribution indicates that ID is not only widely studied in educational disciplines but also holds significant importance in interdisciplinary scientific applications. Table 2 presents the distribution of articles across different subject areas, highlighting the research focus and application breadth of instructional design in various disciplines.

Figure 1 presents the trend in published articles and citations from 1991 to 2024. While there was a slight reduction in publications in 2024, the overall pattern indicates consistent growth in instructional design research within science education, highlighting its ongoing significance and impact within the academic community.

Table 2. Distribution of articles by subject area

Subject Area	Number of Articles	Percentage
Education and Educational Research	614	53.48%
Science Discipline Education	250	21.78%
Computer Science Interdisciplinary Applications	137	11.93%
Other Fields	147	12.81%
Total	1148	100%

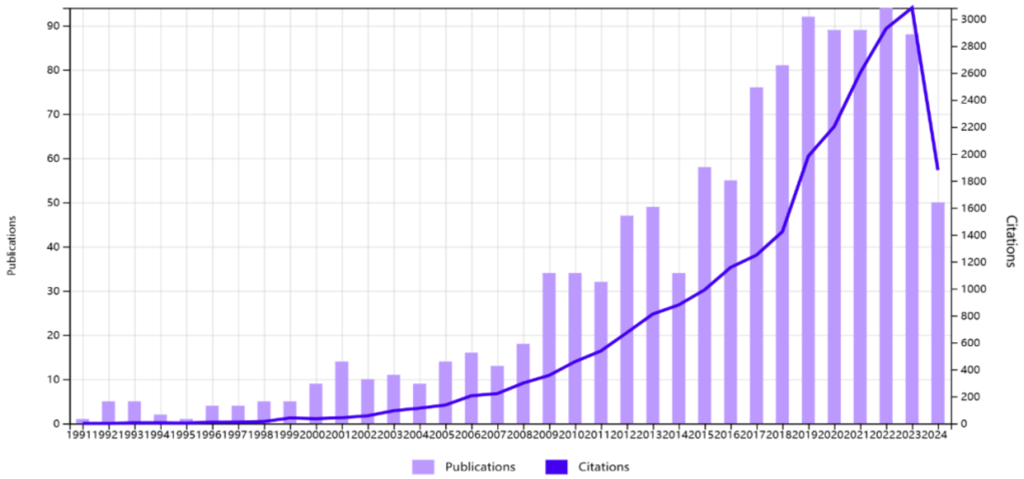

Fig. 1 Trend of publications and citations from 1991 to 2023

3.2 Co-Citation Analysis

A citation threshold of 53 was established for the co-citation analysis, which resulted in the identification of 15 key references. Figure 2 provides an illustration of the comprehensive network analysis derived from these citations. Table 3 presents the top ten co-cited references, ranked according to their total link strength. Among these, Sweller et al. (1998) was cited 67 times, Paas et al. (2003) 55 times, and Sweller (1988) 44 times. Through the co-citation analysis, three distinct thematic clusters were identified and visualized within the network. Each cluster is represented by nodes of the same color, indicating a group of related publications that share common themes (Khanra et al., 2022). A detailed overview of each cluster along with its corresponding tag is provided below.

Cluster 1 (Red) comprises 25 papers centered around the theme of "theoretical frameworks and methodologies in instructional design within the field of science education," exploring how various instructional design theories and methods can optimize teaching effectiveness in science education. It is the largest cluster among the three. Vygotsky and Cole (1978) examined the impact of social and cultural contexts on the learning process, proposing the "sociocultural theory." Ryan and Deci (2000), in their "Self-Determination Theory," found that students' engagement and persistence in learning activities significantly increase when they experience autonomy, competence, and relatedness, providing a theoretical framework for ID in science education. Expanding upon these theoretical bases, several specific teaching methods and strategies have emerged. Merrill (2002) proposed a set of systematic instructional design principles in his *First Principles of Instruction*. Hmelo-Silver et al. (2007) explored the role of scaffolding in problem-based and inquiry learning. Cook (2006) studied the impact of cognitive load theory on visual representations in science education. These methods and strategies significantly enhance students' knowledge acquisition and application skills (Merrill, 2002), inquiry abilities (Hmelo-Sliver et al., 2007), and learning outcomes (Cook, 2006). The application of multimedia and virtual reality in science learning can also increase student engagement and interest, and enhance understanding of complex concepts, although careful design is needed to mitigate cognitive overload (Parong & Mayer, 2018; Sweller et al., 2019). Hattie and Timperley (2007) found that high-quality feedback significantly improves student learning outcomes, especially when the feedback is specific and actionable. Braun and Clarke's (2006) thematic analysis, a systematic qualitative analysis method, helps researchers gain deeper insights into complex educational phenomena and students' learning experiences. In science education, various instructional design theories and methods are widely applied and validated to enhance teaching effectiveness and student learning experiences.

Cluster 2 (Green), consisting of 18 papers, focuses on "Cognitive Load Theory and Instructional Design." This group explores how understanding and applying Cognitive Load Theory (CLT) can optimize instructional design. Sweller et al. (1998) discuss the application of cognitive architecture and CLT in instructional design, emphasizing significance of taking into account students' cognitive load during the design process to enhance learning outcomes by reducing unnecessary cognitive burden and optimizing intrinsic cognitive load. Paas et al. (2003) further highlight that optimized instructional design significantly improves students' learning efficiency and knowledge retention. Beyond optimizing the teaching process, CLT's application in instructional design is also evident in complex learning domains. Sweller (1994) found that optimizing instructional design to reduce unnecessary cognitive load significantly improves student performance in complex learning tasks. De Jong (2010) reflects on the application of CLT in educational research, noting its substantial potential for explaining educational phenomena and guiding instructional design. Applying CLT in instructional design can significantly enhance students' learning outcomes, especially in complex learning tasks. Miller's (1956) influential work on the *magical number seven, plus or minus two* discusses human information processing capacity limits, providing a foundational basis for CLT. Leppink et al. (2013) developed tools to assess various types of cognitive load, facilitating better understanding and application of CLT and providing a scientific basis for instructional design assessment. This cluster focuses on how optimizing cognitive load can enhance instructional design effectiveness, particularly in science education. The findings indicate that effective cognitive load management not only improves students' learning efficiency but also promotes long-term knowledge retention and application.

Cluster 3 (Blue), consisting of 10 papers, addresses "Instructional Design in Multimedia and Complex Learning Environments." These studies explore how to optimize instructional design within multimedia and complex learning contexts to enhance learning outcomes. Moreno and Mayer (1999) examined the underlying principles of multimedia learning, emphasizing the importance of modality (e.g., visual and auditory) and contiguity in enhancing learning effectiveness. They found that appropriate multimodal design can effectively enhance students' learning experiences and outcomes. By integrating multiple sensory inputs, students' attention and engagement can be increased, thus promoting learning (Moreno & Mayer, 2007a). For example, Mayer and Anderson (1992) studied the role of visualization in instruction and found that combining text with animation can help students better understand and remember learning content. However, the inherent limitations of multimedia learning are primarily seen in the excessive information presentation, which can lead to cognitive overload and hinder comprehension. By simplifying information and optimizing presentation methods, students' comprehension and memory can be significantly improved (Mayer et al., 2001). Regarding the management of cognitive load in complex learning environments, Chandler and Sweller (1991) investigated how different instructional design formats affect students' cognitive load and learning performance. They emphasized the importance of format and structure in designing instructional materials and simplifying information presentation. van Merriënboer et al. (2003) proposed a four-component instructional design model (4C/ID) to assist students in more effectively mastering skills in complex learning tasks. Additionally, Kalyuga (2009) studied the expertise reversal effect and found that certain types of instructional support become less effective as learners' knowledge levels increase, suggesting that instructional support should be adjusted according to the learners' levels. This cluster of literature demonstrates various methods for optimizing instructional design in multimedia and complex learning environments. Effective instructional design can not only reduce students' cognitive load but also enhance their learning outcomes and knowledge retention, especially when dealing a with complex and multimodal learning tasks.

Co-citation analysis identified three clusters: theoretical frameworks in science education, CLT in ID, and multimedia and complex learning environments. Table 4 provides a summary of the co-citation analysis, detailing the cluster labels, the number of publications, and the exemplary works within each cluster.

Table 3. Top 10 documents in terms of co-citation analysis and total link strength

No.	Documents	Citation	Total link strength
1	Sweller, J. (1998). Cognitive architecture and instructional design Educational psychology review, 10, 251-296.	67	378
2	Paas, F. (2003). Cognitive load theory and instructional design Recent developments. Educational psychologist, 38(1), 1-4.	55	286
3	Sweller, J. (1988). Load during problem solving: Cognitive Science, 12(2).	44	258
4	Van Merrienboer, J. J., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions Educational psychology review, 17, 147-177.	28	194
5	De Jong, T. (2010). Cognitive load theory, educational research and instructional design: Some food for thought. Instructiona science, 38(2), 105-134.	33	188
6	Kirschner, P. A., & Erkens, G. (2006). Cognitive tools and mindtools for collaborative learning. Journal of Educationa Computing Research, 35(2), 199-209.	43	186
7	Sweller, J. (2019). Cognitive architecture and instructional design 20 years later. Educational psychology review, 31, 261-292.	36	185
8	Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information Psychological review, 63(2), 81.	26	179

No.	Documents	Citation	Total link strength
9	Sweller, J. (1994). Cognitive load theory, learning difficulty, anc instructional design. Learning and instruction, 4(4), 295-312.	28	168
10	Sweller, J. (2011). Cognitive load theory, learning difficulty, anc instructional design. Explor Learn Sci, 3, 3-10.	25	151

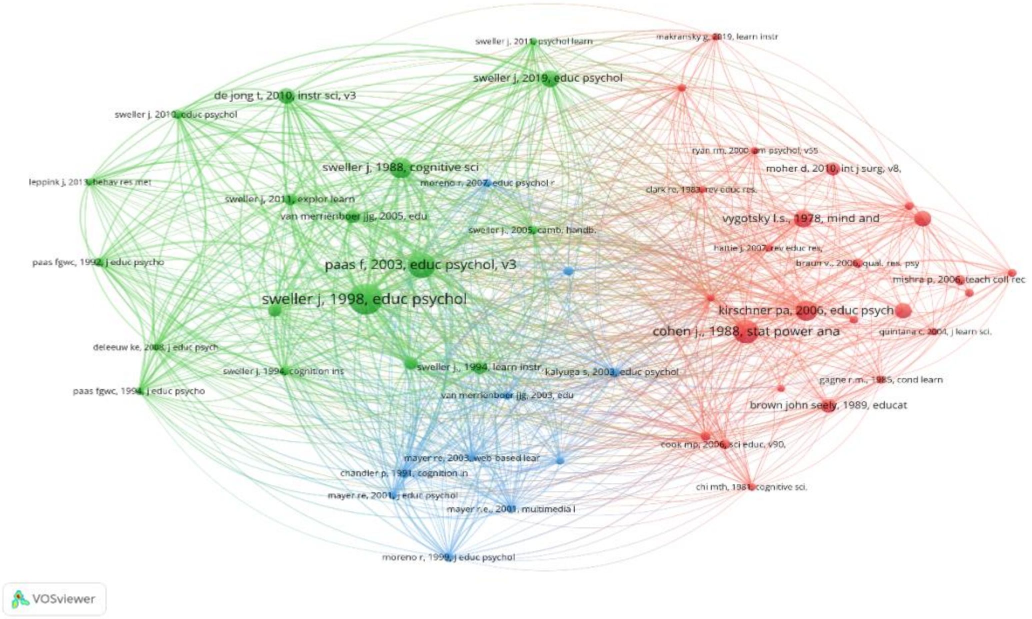

Figure 2. Co-citation analysis (VOSviewer visualization)

Table 4. Co-citation clusters on Instructional Design in Science Education

Cluster	Cluster label	Number of publications	Representative publications
1 (Red)	Theoretical Framework and Methodologies ir Science Education	25	Vygotsky and Cole (1978); Ryan and Dec (2000); Merrill (2002); Hmelo-Silver et al (2007); Ainsworth (2006); National Researc Council (2012); Cook (2006); Clark (1983
2 (Green	Cognitive Load Theory ir Instructional Design	18	Sweller et al. (1998); Paas et al. (2003); De Jong (2010); Sweller et al. (2019); Mille (1956); Leppink et al. (2013); Sweller anc Chandler (1994); Paas and Van Merriënboe (1994)
3 (Blue)	Instructional Design ir Multimedia and Comple Learning Environments	10	Moreno and Mayer (1999); Mayer anc Anderson (1992); Bruning et al. (2003); Va Merriënboer et al. (2003); Kalyuga (2009) Chandler and Sweller (1991)

Source. Author’s interpretation derived from VOSviewer analysis

3.3 Co-Occurrence of Keyword

Conducting a co-word analysis on the 4506 keywords found within this collection, we identified at least 20 different combinations with a minimum of 61 occurrences each (Figure 3). Each node signifies a keyword (or topic). The frequency of co-occurrence in published papers is depicted by the thickness of the lines connecting the nodes, which indicates the strength of their association. The co-word analysis revealed that "science" is the keyword that appears most frequently, appearing 294 times, succeeded by "instructional design" (256 occurrences), "education" (194 occurrences), and "student" (150 occurrences). Table 5 highlights the top 15 co-occurring keywords in this study. The subsequent analysis and discussion are structured around the four prominent clusters identified in Figure 3:

Cluster 1 (Red): The first cluster, encompassing 18 keywords, centers around "Technology-Enhanced Science Education." Keywords such as "augmented reality", "virtual reality", and "online learning" indicate that this cluster's research focuses on how modern technological tools can be leveraged to improve science education and enhance student learning experiences and outcomes. For instance, enhanced reality and immersive virtual environments are widely used in science education to supply more immersive and interactive learning experiences. Moreno and Mayer (2007b,1999) explored the cognitive principles of multimodal learning environments and found that appropriate multimodal design significantly enhances students' learning experiences and outcomes. These technological applications necessitate careful instructional design to manage cognitive load and optimize information presentation. Studies have demonstrated that well-designed online learning environments can effectively manage students' cognitive load and enhance learning results (Mayer et al., 2001). Blended learning, integrating traditional classroom instruction with online methods, provides a flexible and efficient environment for learning. This method has been demonstrated to enhance student motivation and performance (Bruning et al., 2003). In higher education, the enhancement and optimization of science education remain a primary focus. Modern technological tools like virtual labs and online resources can enrich science education content in higher education (National Research Council, 2012). Inquiry-based learning and its evaluation of impact are also crucial research areas in science education. While inquiry-based learning strengthens students' critical thinking and scientific inquiry skills, impact assessment provides educators with insights into the true effectiveness of these approaches (Chi et al., 1981). Additionally, collaborative learning is considered an essential approach in science education to enhance students' comprehension and application of knowledge. Through collaboration, students can share knowledge, learn from each other, and improve their problem-solving skills (Hmelo-Silver et al., 2007). Overall, technology-enhanced science education demands innovative instructional design to account for the unique characteristics of technological applications and manage cognitive load effectively, aiming for optimal teaching outcomes and learning experiences.

Cluster 2 (Green): The second cluster, consisting of 16 keywords, centers on "Cognitive Load and Instructional Design," exploring how applying CLT can optimize instructional design to improve learning outcomes. The core concept of CLT is to manage different types of cognitive load during the learning process: intrinsic cognitive load, extraneous load, and germane cognitive load. Sweller et al. (1998) and Sweller (2010) emphasize that optimizing ID to reduce extraneous load and enhance intrinsic load can significantly improve learning outcomes. Investigations reveal that adhering to CLT principles in instructional design can markedly enhance learning effectiveness. Paas et al. (2003) discuss how instructional design can reduce students' cognitive load. Sweller and Chandler (1994) highlight the importance of simplifying and optimizing information presentation to enhance instructional effectiveness. Multimedia learning is widely used in science education, but it also poses challenges in managing cognitive load. Moreno and Mayer(2007b) investigate the cognitive principles underlying multimedia learning, highlighting how modality and contiguity play a crucial role in minimizing cognitive load and improving learning outcomes. Appropriate multimodal design can significantly improve students' learning experience and outcomes. Simulations are increasingly used in science education, providing virtual experimental environments that can reduce cognitive load associated with real-world experiments. Kalyuga (2009) examines the expertise reversal effect, finding that as learners' knowledge levels increase, the efficacy of specific forms of instructional support decreases, indicating the need to adjust instructional design based on learners' levels. High-quality feedback plays a crucial role in instructional design. Hattie and Timperley (2007) find that specific and actionable feedback can significantly enhance students' learning outcomes. Feedback helps students understand their progress and guides them in improving their learning strategies. To better understand the application of CLT in ID, many studies have conducted meta-analyses and reviews to summarize and evaluate existing research findings.

Cluster 3 (Blue): The third cluster, encompassing 15 keywords, focuses the integration of "Pedagogical Content Knowledge (PCK) and E-Learning Design," emphasizing the importance of effective instructional frameworks and analytics in enhancing science education. E-learning, as an emerging educational model, is increasingly being applied in science education. Well-designed online courses can effectively improve student learning outcomes and engagement (Bruning et al., 2003). Effective instructional design requires the integration of theoretical support and practical frameworks. Therefore, developing robust instructional frameworks that combine PCK with modern e-learning methods is crucial. Koehler et al. (2013) discussed the TPACK framework, which extends PCK to include technological knowledge, providing a comprehensive model for effective teaching. Teachers using the TPACK framework are better able to integrate technology, enhancing student learning outcomes. Effective instructional design in e-learning involves creating engaging and interactive learning experiences. Means et al. (2014) studied various online learning models and their effectiveness in promoting student learning. The results indicated that project-based online learning models significantly improve students' self-directed learning abilities and knowledge application skills. Additionally, teachers' beliefs and perceptions significantly influence their adoption and implementation of innovative teaching practices. Fives and Gill (2014) found that instructors with affirmative beliefs are more inclined to implement student-centered teaching approaches, thereby enhancing student learning outcomes and engagement. This highlights the significance of ongoing support and professional development for teachers. Teachers who participate in continuous professional development are more innovative in their classrooms, leading to improved student learning outcomes (Darling-Hammond et al., 2017). Overall, this cluster emphasizes the integration of PCK with innovative learning design principles in e-learning environments to enhance the effectiveness of science education.

Cluster 4 (Yellow): The fourth cluster, which includes 12 keywords, centers on focuses on "Computational Thinking and STEM Education," exploring how effective instructional strategies can enhance students' computational thinking abilities, engagement, and learning outcomes in STEM education. Computational thinking is a significant area in modern education, emphasizing the development of problem-solving skills through algorithms, decomposition, and pattern recognition. In computer science education, computational thinking has been widely applied and is considered a key skill for students' future success in the technology sector. For example, Wing (2006) proposed that computational thinking is not just about programming but a problem-solving approach that is applicable across multiple disciplines. In STEM education, the incorporation of computational thinking helps improve students' learning outcomes in mathematics and science. Research indicates that incorporating computational thinking into math and science curricula can significantly enhance students' self-efficacy and motivation. Brennan and Resnick (2012) found that students participating in computational thinking courses excelled in solving complex problems and demonstrated innovative thinking. Active learning is a critical strategy for improving student engagement and achievement. Freeman et al. (2014) demonstrated that active learning strategies notably enhance student performance in STEM courses, particularly in large classroom environments. Effective instructional strategies are crucial for increasing student engagement and learning outcomes in STEM education. Teachers can design interactive and content-rich courses to stimulate students' interest in learning. For instance, Stohlmann et al. (2012) suggested that integrating interdisciplinary instructional strategies enables students to understand STEM concepts more comprehensively and utilize them in real-world situations. Within the framework of instructional design in science education, this implies the need to develop powerful instructional frameworks that combine computational thinking with modern e-learning methods. By integrating Pedagogical Content Knowledge (PCK) with contemporary e-learning techniques, teachers can develop captivating and impactful courses that enhance students' learning experiences and outcomes. Overall, this cluster highlights the significance of integrating computational thinking and effective instructional strategies in STEM education to enhance students' learning experiences and outcomes. These findings suggest that computational thinking is not only central to programming education but also a broadly applicable problem-solving method that lays a solid foundation for students' future development.

Key thematic clusters in the field are identified through the co-word analysis. Specifically, Table 6 presents the findings from the co-word analysis for instructional design within the context of science education.

Table 5. The 15 most frequent keywords in the keyword co-occurrence analysis.

Rank	Keyword	Occurrences	Total link strength
1	Science	294	915
2	Instructional design	256	612
3	Education	194	581
4	Students	150	545
5	Instructional-design	129	380
6	Knowledge	103	316
7	Performance	98	306
8	Design	83	246
9	Technology	76	283
10	Framework	68	231
11	Cognitive load	64	247
12	Learning design	60	133
13	Cognitive load theory	54	187
14	Model	54	181
15	Impact	51	164

Table 6. Co-word analysis on Instructional Design in Science Education

Cluster No and colour	Cluster label	Number of keywords	Representative Keywords
1 (Red)	Technology-Enhanced Science Education	18	"attitudes," "augmented reality," "blended learning," "challenges," "classroom," "collaboration," "education," "environments," "experiences," "higher education," "impact," "inquiry," "online learning," "science education," "science-education," "technology," "virtual reality."
2 (Green)	Cognitive Load & Instructional Design	16	"acquisition," "cognitive load," "cognitive load theory," "feedback," "information," "instructional design," "knowledge," "learning," "memory," "meta-analysis," "multimedia," "performance," "principles," "simulation," "skills."
3 (Blue)	PCK & E-Learning Design	15	"beliefs," "design," "e-learning," "framework," "instruction," "learning analytics," "learning design," "model," "online," "pedagogical content knowledge," "perceptions," "science," "support," "teachers," "thinking."

Cluster No and colour	Cluster label	Number of keywords	Representative Keywords
4 (Yellow)	Comp Thinking & STEM Strategies	12	"achievement," "active learning," "computational thinking," "computer science education," "curriculum," "engagement," "mathematics," "motivation," "self-efficacy," "stem education," "strategies," "students."

Source. Author's interpretation derived from VOSviewer analysis

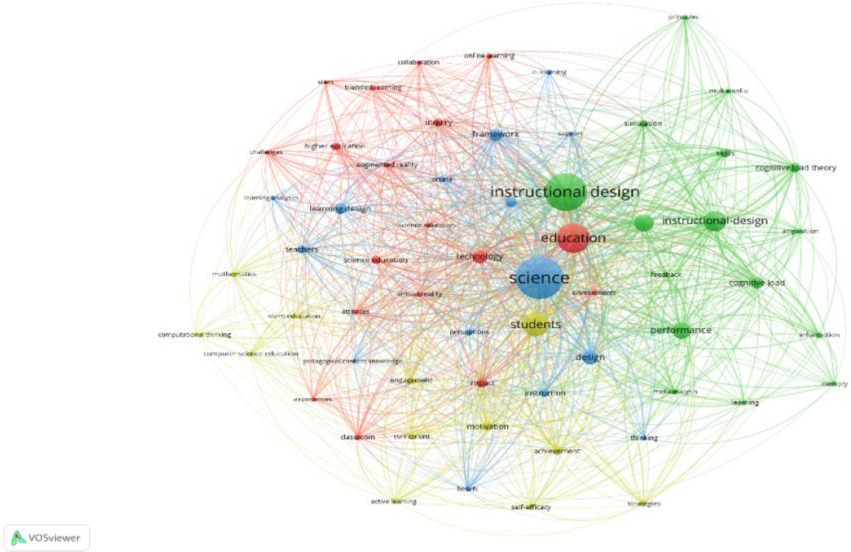

Fig. 3 Co-word analysis of instructional design in science education (VOSviewer visualization).

3.4 Implications

3.4.1 Theooretical implications

Theoretical implications for ID in science and science education, derived from co-citation and co-word analyses, are profound. The co-citation analysis reveals a solid theoretical basis, grounded in established frameworks like Vygotsky's theory of sociocultural development and Ryan and Deci's theory of self-determination. This highlights the critical role of social context and intrinsic motivation in shaping effective instructional design strategies within scientific learning environments. Moreover, the prominence of cognitive load theory revealed by co-citation analysis emphasizes the importance of optimizing cognitive processes to enhance learning outcomes, particularly in complex and multimedia-rich educational settings. These insights suggest that future instructional designs should prioritize strategies that minimize cognitive overload while maximizing information retention and comprehension. Complementing these findings, the co-word analysis underscores an increasing emphasis on integrating technology-enhanced learning methods and computational thinking into STEM education (Ní Shé et al., 2023; Wu, 2024). This trend reflects a growing recognition of the value of advanced technological tools and interdisciplinary approaches in promoting deeper understanding and engagement among students. Furthermore, active learning techniques highlighted by the co-word analysis emphasize their pivotal role in fostering student engagement and achievement within science education. Collectively, these insights advocate for future research endeavors to focus on developing theoretically grounded instructional designs enriched with technology while prioritizing cognitive optimization to maximize student learning experiences across various scientific disciplines.

3.4.2 Practical implications

Based on the results of this study, the practical implications for ID in the field of science and science education are multifaceted. The strong theoretical foundation highlighted in the study highlights the significance of integrating well-established frameworks into instructional design. This integration can enhance the effectiveness of instructional strategies by leveraging social context and intrinsic motivation to create more engaging and supportive learning environments. The emphasis on cognitive load theory reveals the necessity of optimizing cognitive processes to improve learning outcomes. Instructional designs should thus focus on minimizing cognitive overload while enhancing information retention and comprehension, especially in complex and multimedia-rich settings. Moreover, the trend towards incorporating technology-enhanced learning methods and computational thinking into STEM education is particularly notable. This reflects a growing recognition of the value of advanced technological tools and interdisciplinary approaches in fostering deeper understanding and engagement among students (Ní Shé et al., 2023; Wang et al., 2022). Effective instructional designs should incorporate these technological advancements to create immersive and interactive learning experiences that enhance students' problem-solving skills and motivation. Furthermore, the importance of active learning techniques in enhancing student achievement and engagement within science education cannot be overstated. Techniques like inquiry-based learning and project-based learning have been shown to significantly improve student performance and participation. By implementing these strategies, educators can develop adaptable and engaging learning environments that address the varied needs of students. Overall, these insights advocate for future research to develop instructional designs that are theoretically grounded and enriched with technology, prioritizing cognitive optimization to maximize student learning experiences across various scientific disciplines. This approach not only supports immediate educational outcomes but also prepares students for future challenges by equipping them with essential skills and knowledge.

The theoretical and practical implications of this research underscore the importance of integrating advanced technological tools, managing cognitive load, and employing active learning strategies in instructional design for science education. These findings advocate for the development of instructional designs that effectively leverage technology, optimize cognitive processes, and foster student engagement to enhance learning outcomes. Collectively, these insights provide a solid foundation for future research and practical applications aimed at improving science education through innovative and effective instructional practices.

4. Conclusion, Limitations and Future Directions

This bibliometric analysis delivers a solid foundation for understanding the primary themes and advancements in instructional design within science education. It identifies significant clusters representing theoretical frameworks, cognitive load management, multimedia learning environments, and computational thinking, highlighting their rapid evolution and impact on educational practices. The co-citation analysis identifies three significant clusters within the domain of instructional design for science education and science. These clusters provide a comprehension of both the theoretical and practical dimensions of instructional design. They advocate for strategies that incorporate cognitive theories and technological advancements to enhance science education outcomes.

The first cluster highlights the transformative potential of technology-enhanced science education. Advanced tools like augmented reality, virtual reality, and online learning platforms allow educators to create dynamic, interactive environments that make abstract scientific concepts more tangible and engaging. These technologies facilitate immersive learning experiences, enabling students to visualize and manipulate scientific phenomena in ways traditional methods cannot. Blended learning, which integrates in-person teaching with digital tools, offers a flexible and efficient approach to education, enhancing student motivation and performance. Additionally, inquiry-based and collaborative learning approaches foster critical thinking, scientific inquiry skills, and teamwork. Overall, the findings emphasize the need for innovative instructional designs that leverage technology to manage cognitive load and improve learning outcomes in science education.

The second cluster centers on the application of CLT in optimizing instructional design. This group highlights the significance of managing cognitive load to enhance learning outcomes, especially through the reduction of extraneous cognitive load and the optimization of intrinsic cognitive load. The application of CLT extends to complex learning tasks, where it significantly improves performance by managing element interactivity and different cognitive loads. Tools developed to measure cognitive load aid in better understanding and applying CLT principles, ensuring more effective instructional designs. The findings highlight that efficient cognitive load management enhances learning efficiency, retention, and application, particularly in science education.

The last cluster focuses on optimizing instructional design in multimedia and complex learning environments. It highlights the importance of multimodal design, integrating visual and auditory elements to enhance learning experiences. Studies demonstrate that combining text with animation and managing cognitive load can significantly improve comprehension and memory. Effective instructional designs reduce cognitive overload and increase student engagement and performance, particularly in web-based and complex learning contexts. This cluster emphasizes the need for structured instructional formats and adaptive support to match learners’ knowledge levels, ensuring enhanced learning outcomes and knowledge retention.

On the other hand, the co-word analysis reveals four key thematic clusters in the research of instructional design in science education, each focusing on different research directions and hot topics. Firstly, the “Technology-Enhanced Science Education” cluster emphasizes the application of modern technological tools (such as virtual reality, augmented reality, and online learning) in improving science education and enhancing student learning experiences and outcomes. Secondly, the “Cognitive Load Management and Optimized Instructional Design” cluster explores the importance of applying CLT to optimize instructional design and improve learning outcomes. Thirdly, the “Integration of Pedagogical Content Knowledge (PCK) and E-Learning Design” cluster highlights the necessity of combining PCK with modern e-learning methods in electronic learning environments to enhance the effectiveness of science education. Lastly, the “Instructional Strategies in Computational Thinking and STEM Education” cluster focuses on the research of effective instructional strategies to enhance students’ computational thinking abilities, engagement, and learning outcomes in STEM education. Overall, the co-word analysis provides a comprehensive research perspective on instructional design in science education, emphasizing the importance of optimizing instructional design through cognitive theories and technological advancements. These findings not only guide current instructional practices but also offer valuable references for future research directions.

The bibliometric analysis presented in this review provides a comprehensive foundation for understanding the trends and applications of ID within the domain of science education. The co-citation and co-word analyses identified key theoretical frameworks, methodologies, and emerging themes that shape the current landscape of ID research. This review highlights the importance of integrating established theories like sociocultural theory and cognitive load theory alongside modern technological advancements to improve teaching effectiveness and enrich student learning experiences in science education. Nevertheless, this study has its limitations. The reliance on bibliometric data may overlook nuanced insights and recent developments not yet widely cited. Additionally, the scope of the databases used could limit the comprehensiveness of the literature included.

Future research should focus on developing and testing innovative instructional designs that leverage technology to optimize cognitive load and engagement. Longitudinal studies assessing the impact of these designs on student outcomes across diverse educational settings will be essential. Exploring interdisciplinary approaches that integrate computational thinking and active learning strategies can further advance the field. These efforts will ensure that instructional design in science education remains responsive to the evolving educational landscape and the needs of diverse learners.

5. Co-Author Contribution

The authors affirm that there is no conflict of interest in this article. **Chen Wang** carried out the field work, prepared the literature review, and oversaw the overall writing of the article. **Rohana Yusof** was responsible for writing the research methodology and performing the data entry. **Eng Tek Ong**

conducted the statistical analysis and interpreted the results. All authors have sufficiently contributed to the study and agreed with the results and conclusions.

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