

Research Hotspots and Trend Analysis in AI-Enabled Accessible Design: Identification of Core Areas, Evolution of Future Trends, and Visualization through Knowledge Graphs

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Abstract

This paper utilizes the Web of Science Core Collection (2000–2025) as its data source and employs an integrated analytical approach comprising bibliometrics, burst detection, and knowledge mapping to systematically review the research status, core structures, and emerging trends in the domain of artificial intelligence–enhanced accessible design. The findings indicate that this field has undergone a three-stage evolution characterized as exploration, coupling, and integration, with the volume of research consistently expanding. This growth has established a triadic backbone consisting of XR media, the Universal Design for Learning (UDL) paradigm, and interaction evaluation (UX/HCI/assistive technologies). This framework advances research from engineering feasibility toward contextual practicality. Keyword clustering reveals a five-ring structure encompassing educational accessibility, inclusive design, XR technologies, and governance norms, with frontier hotspots focused on the applications of generative and multimodal AI, the standardization of XR accessible interfaces, and meta-analysis–oriented evidence synthesis. The collaboration network exhibits a strong-center, long-tail characteristic, with North American and European institutions at its core, while the Asia–Pacific region emerges as a growth pole. The study constructs a User–Scenario–Technology (UST) × lifecycle (needs, design, deployment, evaluation, governance) knowledge framework and elucidates the paradigm-shift pathway from technical effectiveness to contextual usability and trustworthy governance. This paper provides systematic evidence and outlines future research directions for the standardized application and sustainable governance of AI-enabled accessible design.

1. Introduction

Accessible design is a systematic approach that ensures products, environments, and information systems are accessible, usable, and inclusive for the widest possible range of individuals (Persson et al., 2015). This includes people with disabilities, older adults, those with temporary limitations, and the general population, without requiring subsequent retrofitting (Persson et al., 2015). According to statistics from the World Health Organization, the global population of individuals with disabilities has surpassed 1 billion, representing over 15% of the total population (Organization, 2020). Additionally, the proportion of older adults is projected to continue increasing in the future (see Fig. 1). With the accelerating global population aging, the rising number of individuals with disabilities, and the ongoing digitalization of society, accessible design has become a critical issue for equity, inclusion, and sustainable development (Pulsiri et al., 2019). In response, countries and international organizations have strengthened legislation and policies—such as the Convention on the Rights of Persons with Disabilities and the 2030 Agenda for Sustainable Development—and have promoted the practice of empowerment and accessibility for all (Mishra et al., 2023). In recent years, a variety of AI-enabled technologies—including speech recognition, image understanding, natural language processing, augmented and virtual reality, and intelligent assistive devices—have been widely implemented in smart healthcare (Khalid et al., 2024), inclusive education, accessible transportation, smart homes, digital cities, and cultural services, significantly enhancing the accessibility and personalization of products, environments, services, and information systems. AI-driven emerging directions—such as multimodal interaction, affective

computing, and collaborative innovation—are continuously expanding the boundaries of accessible design(Pandey, 2025). These advancements promote a more inclusive and participatory social ecosystem for individuals with disabilities, older adults, people with temporary limitations, and, indeed, all marginalized groups.

Existing research indicates that artificial intelligence (AI), through technologies such as speech and vision recognition, natural language processing (NLP), augmented reality (AR), virtual reality (VR), generative models, and intelligent assistive devices, is creating new pathways for accessibility in education and healthcare rehabilitation. Methodologically, Miraz et al. (2021) propose the concept of supported by ability profiling, context sensing, and cross-device migration(Miraz et al., 2021). They argue that interfaces should be both adaptable and adaptive, thereby transforming accessibility from a one-time accommodation into an ongoing collaboration between humans and computers. From a complementary perspective(Miraz et al., 2021), Ritvo and Allison (2016) critique the implicit bias embedded in the foundations of human-computer interaction (HCI) and advocate for incorporating broader user diversity from the outset of design(Ritvo & Allison, 2017). They emphasize the importance of long-term participatory design, redirecting accessibility research toward a human-centered approach in which diversity is the norm(Ritvo & Allison, 2017). The human-computer interaction framework addressing societal issues advocates for the comprehensive integration of value-sensitive design and multi-stakeholder participation. It emphasizes the need to simultaneously consider technology, ethics, and governance (HCI and Societal Issues: A Framework for Engagement)(Ritvo & Allison, 2017). Regarding educational and learning accessibility, Universal Design for Learning (UDL) is widely recognized as a methodological foundation that organizes multimodal support through a "goals–representation–action" framework (Staats & Laster, 2018). Moreover, advancements in multimodal recognition, as well as wearable and mobile interactions, have significantly enhanced attention, communication, and feedback in both classroom and remote learning environments (Day et al., 2021; Martin-Gutierrez & Del Rio Guerra, 2021; Yuan et al., 2023). Systematic reviews indicate that combining artificial intelligence (AI) with serious games can enhance children's motivation and adherence in speech rehabilitation(Tolks et al., 2024). However, most studies are limited to short cycles and laboratory settings, with evaluations primarily focusing on This emphasis results in insufficient attention to indicators related to affect, motivation, and social experience, as well as a lack of real-world longitudinal evidence (Abdoulqadir and Loizides, 2025)(Abdoulqadir & Loizides, 2025). In the context of supporting cognitive and social impairments, co-creation–led virtual reality (VR) multi-user collaborative training has improved contextual fit and social outcomes for adolescents on the autism spectrum. Nonetheless, it underscores the need to address constraints such as cybersickness, collaborative accessibility, and safety boundaries during early design stages to avoid patchwork retrofits later (Gabrielli et al., 2023) (Gabrielli et al., 2023). Applied studies in medical and care settings indicate that mobile platforms and edge intelligence offer promising pathways for accessibility assessments in low-resource and time-sensitive environments(Gabrielli et al., 2023; He et al., 2024). For individuals with cerebral palsy who are unable to communicate verbally, AI-driven mobile solutions have enhanced the objectivity and accessibility of pain recognition (Sabater-Garriz et al., 2025)(Sabater-Gárriz et al., 2025). Concurrently,

applied engineering research demonstrates that multimodal sensor fusion, edge inference, and energy efficiency optimization can significantly reduce deployment barriers in both community and clinical settings (Trigka & Dritsas, 2025; Zulkifli & Nurhaliza). However, these approaches remain limited in terms of data representativeness, cross-institutional interoperability, and evidence of longitudinal adherence (Applied Sciences, 2021; Electronics, 2023; Sensors, 2021) (Jeong et al., 2021; Martin-Gutierrez & Del Rio Guerra, 2021; Yuan et al., 2023). Within the domain of immersive interfaces and standardization efforts, Creed et al. (2023) systematically propose a research agenda for inclusive augmented reality (AR) and virtual reality (VR) (Creed et al., 2024). They identify four primary challenges to immersive accessibility: software usability, hardware usability, collaborative interaction, and ethical governance (Creed et al., 2024). Furthermore, they advocate for the development of unified application programming interfaces (APIs) and cross-device consistency standards for features such as captioning, audio description, sign language, and haptic feedback (Creed et al., 2024). This aims to facilitate a shift from fragmented prototypes toward industry-grade standardization and scalable deployment (Amaxilatis et al., 2020). Creed et al. further employed a 'Sandpit' co-creation approach to develop a comprehensive 49-item list of barriers and assessment elements. This work underscores the necessity of reconstructing standards and evaluation metrics for immersive accessibility by engaging multiple stakeholders in the co-creation process (Creed et al., 2024). From an organizational policy perspective, Vijaya et al. (2024) highlight a significant tension within Indian workplaces, described as 'advanced policies, lagging practice.' They argue that enterprises largely remain at a compliance-driven level of superficial inclusion, lacking standardized closed-loop evaluation and effective multi-party coordination (Vijay et al., 2024).

Despite significant advancements in existing research across various dimensions—methodological innovation, contextualized application, and engineering standardization—there remains a notable lack of systematic coordination grounded in bibliometric evidence. Few studies effectively integrate bibliometrics with scientific knowledge mapping to present, through a unified perspective, both the current landscape and emerging research frontiers of the field. Furthermore, these studies often fail to develop actionable conceptual frameworks or propose forward-looking research agendas based on their findings. This gap results in difficulties aligning interdisciplinary outcomes, a lack of evidence for thematic evolution, and engineering and governance recommendations that lack reusable chains of evidence. To address this issue, this paper utilizes the Web of Science Core Collection (2000–2025) as the data source and adopts an integrated "bibliometrics–knowledge mapping" approach to systematically depict scale dynamics, collaboration structures, knowledge bases, and frontier topics. Furthermore, it reconstructs a conceptual knowledge graph along the coordinates of "User–Scenario–Technology (UST) × lifecycle (needs–design–deployment–evaluation–governance)," clarifies the transition pathway from "technical effectiveness" to "contextual usability and trustworthy governance," and proposes actionable agendas for interface standardization, data compliance, and long-term real-world evaluation.

Based on the background and practical challenges outlined above, this study focuses on four core research questions:

RQ1: How has the scale of research on AI-enabled accessible design evolved from 2000 to 2025?

RQ2: Which authors, institutions, and countries have established significant influence and collaboration networks in this field?

RQ3: What are the primary research themes and the knowledge structure associated with AI-enabled accessible design?

RQ4: What new research trends have emerged in the frontier hotspots and emerging topics in recent years?

This study employs systematic bibliometric and knowledge-graph analyses of literature from the Web of Science Core Collection, covering the period from 2000 to 2025. It reveals the overall structure, thematic evolution, and emerging trends in AI-enabled accessible design. This research addresses the scholarly gap caused by the lack of systematic reviews in this field and constructs a five-layer knowledge framework consisting of empowerment—methodological paradigm—scenario deployment—evaluation and governance—value guidance. This framework clarifies the core pathway of 'XR media + UDL paradigm + interaction evaluation(Lazou & Tsinakos, 2025; Zaugg, 2024). The findings are highly valuable for advancing the standardized implementation of AI technologies in educational, rehabilitative, and urban accessibility settings(Brotosaputro et al., 2024; Chalkiadakis et al., 2024). Furthermore, they offer both theoretical foundations and practical guidance for future advancements in multimodal AI, the standardization of XR accessibility interfaces, and governance frameworks focused on fairness and transparency(Kourtesis, 2024; Lifelo et al., 2024).

2. Materials and Methods

2.1 Data Sources and Search Strategy

This study utilizes the Web of Science (WOS) Core Collection database as its exclusive data source. WOS encompasses multiple disciplinary fields, including natural sciences, engineering and technology, social sciences, and humanities, and is renowned for its high academic rigor and wide recognition(Chavarro et al., 2018; Van Leeuwen, 2013). To ensure interdisciplinary coverage and comparability of citation data, our search strategy centers on two core themes: 'artificial intelligence' and 'accessible design.' To comprehensively cover the relevant literature, we expanded the thematic expressions in the keyword design (see Table 1). Boolean operators were employed during the retrieval process: 'AND' connected the two thematic domains, while keywords within each domain were linked by 'OR.' To ensure interdisciplinary coverage and comparability of citation data, the search field was restricted to TS=Topic. The retrieval time window was set from January 1, 2000, to August 1, 2025, with the language limited to English, resulting in an initial total of 571 records.

Table 1
Search Keywords.

TS	Search Terms
Artificial Intelligence	"artificial intelligence" OR "AI" OR "digitalization" OR "AI-generated content" OR "AIGC" OR "digital design" OR "digital innovation" OR "computer vision" OR "digital technology" OR "digital twin technology" OR "human-computer interaction" OR "AI and big data integration" OR "intelligent data processing" OR "intelligent manufacturing" OR "augmented reality" OR "AR" OR "virtual reality" OR "VR" OR "immersive experience design" OR "augmented reality experience" OR "user immersion" OR "interactive narrative" OR "digital installation art" OR "immersive narrative technology" OR "artificial general intelligence" OR "AGI" OR "interaction design" OR "automated design generation" OR "generative model" OR "AI-generated art" OR "generative design" OR "image synthesis" OR "real-time generation" OR "intelligent code generation" OR "digital transformation" OR "artificial intelligence in digitalization" OR "blockchain technology" OR "algorithmic generation" OR "human-AI co-creation" OR "automated content generation" OR "emotional interaction design" OR "data visualization design" OR "parametric design" OR "mathematical modeling" OR "form-finding algorithms"
Accessible Design	"Accessible Design" OR "Barrier-free Design" OR "Inclusive Design" OR "Universal Design" OR "Design for All" OR "Human-centered Inclusive Design" OR "Disability-inclusive Design" OR "Accessibility in Architecture" OR "Accessible Interface Design" OR "Accessibility in Digital Products" OR "Aging-friendly Universal Design" OR "Inclusive Product Design" OR "Universal Design in Public Spaces" OR "Ergonomic Accessible Design" OR "Aging-friendly Design" OR "Design for the Elderly" OR "Child-centered Design" OR "Intergenerational Design" OR "Assistive Design" OR "Visual Impairment Design" OR "Hearing Impairment Design" OR "Digital Accessibility" OR "Inclusive UX Design" OR "Web Accessibility Design" OR "AR/VR Accessibility Design" OR "Sustainable Universal Design" OR "Universal Design and AI"

To enhance the specificity of the study, we selected only articles and proceeding papers as document types, excluding review articles (32), early access publications (21), editorial materials (4), retracted publications (3), book Chaps. (1), and meeting abstracts (1). This resulted in a total of 523 records. Initially, given that the original search expression had broad coverage and potentially high noise, we conducted a dual independent screening of titles and abstracts, followed by adjudication by a third reviewer (Gusenbauer & Haddaway, 2020). We retained only those records that met three specific criteria: (i) they explicitly adopted or investigated AI technologies; (ii) their research objectives focused on accessibility (including inclusive or universal design) for products, environments, or information systems; and (iii) they specified an identifiable target population (such as persons with disabilities, older adults, or individuals with temporary limitations) or a contextual task (including education, medical rehabilitation, web interfaces, XR, or urban workplaces) (Wang et al., 2020). We manually filtered out 99 irrelevant records, resulting in a final set of 424 articles. The data retrieval process is illustrated in Fig. 2.

2.2 Research Methods

This study employs an integrated technical approach that combines bibliometrics with scientific knowledge graphs. The bibliometric method utilizes a range of indicators, including total publications, citations, the h-index, and other related metrics (Costas & Bordons, 2007; García-Villar & García-Santos, 2021), originally proposed by Garfield and Sher. Durieux and Gevenois categorized these indicators into

three groups: quantitative (scientific productivity), relevance (citation impact and the h-index), and structural (collaborative links within a research field)(Durieux & Gevenois, 2010). First, at the bibliometric level, we use Microsoft Excel 2021 to generate a time-series summary of annual publication counts and to calculate average citations per paper, the h-index, and the proportion of highly cited papers, while also compiling data on journals and subject areas(Durieux & Gevenois, 2010). Second, at the collaboration and conceptual structure level, we employ VOSviewer 1.6.20 to construct and visualize three-layer co-authorship networks (including authors, institutions, and countries) as well as a keyword co-occurrence network. To illustrate the geographical distribution of international collaboration, Scimago Graphica is used to create an inter-country collaboration map, which serves solely for geographic visualization and is not included in the network metric calculations.

Thirdly, at the level of intellectual structure and frontier identification, we utilize CiteSpace 6.4.R1 to construct co-citation networks of documents, authors, and journals based on references. We implement main-path and key-path identification to illustrate the knowledge backbone. Additionally, by combining Kleinberg burst detection with source overlay visualization, we uncover key turning points and emerging topics. Finally, during the map integration and figure output stage, we use the networks and temporal diagrams generated by VOSviewer and CiteSpace, employing Adobe Illustrator 2025 for layout unification and annotation fine-tuning, ensuring that the typesetting does not alter the metric results. This workflow guarantees the reproducibility of results, cross-tool corroboration, and consistency in parameter specifications, thereby providing methodological support for subsequent systematic analyses of collaboration patterns, knowledge bases, hotspot evolution, and conceptual frameworks.

3. Results

3.1 Analysis of Publication Trends

The publication trend chart clearly illustrates the annual changes in output volume within the field of “AI-enabled accessible design.” This visualization helps to understand the overall development and stage characteristics, while also serving as a reference for short-term trend analysis. The analysis is based on yearly data from 2000 to 2025 (with data collected up to 2025, including a partial year), encompassing a total sample size of $N = 424$ (see Fig. 3).

The results indicate that there has been a long-term increase in annual publications, with a notable acceleration observed over the past five years. The cumulative curve approximates exponential growth, as evidenced by the fitted equation $y = 0.3274 x^{1.9401}$, with an R^2 value of 0.9161, indicating a strong goodness of fit. The time series can be divided into four distinct stages: ① Nascent Period (2000–2015), characterized by a low output of 0–3 papers per year with a gradual increase, primarily focusing on early explorations of accessibility and assistive technologies; ② Growth Period (2016–2019), during which annual publications consistently reached double digits and continued to rise, with artificial intelligence technologies (such as computer vision, natural language processing, augmented reality, and virtual reality) becoming increasingly integrated into accessibility applications; ③ High-Level Breakout Period

(2023–2025), marked by a rapid surge and fluctuations at a high level (e.g., 2023 = 50, 2024 = 92), broadly aligning with breakthroughs in generative and multimodal AI, as well as advancements in immersive accessibility interfaces. Regarding cumulative scale, the total number of publications increased from 283 in 2023 to 372 in 2024, indicating a substantial uplift and suggesting that the discipline has entered a phase of rapid growth. The field has transitioned from a state of 'fragmented exploration' to one of 'rapid expansion,' with a significant increase in volume observed between 2023 and 2024. In the short term, it is anticipated that this high level of activity is expected to be sustained.

3.2 Analysis of High-Impact Authors

Analyzing author contributions can illuminate the current state of scholarly development within the field, identify prominent researchers and their academic influence, and provide deeper insights into the collaboration networks among researchers (see Table 2). In this context, an analysis of authors with three or more publications reveals a pattern characterized by a 'pronounced head and a dispersed long tail' in terms of output and impact. First, in terms of output, Baldiris and Silvia each authored five papers, making them the most prolific authors in the sample. Following them, most authors produced three to four papers (e.g., Goodman with four, and most others with three), indicating that authors in this field generally publish at small to medium scales. Second, regarding citations, Baldiris notably leads with 136 citations, while Sarcar and Sayan, with three papers and 93 citations, exemplify a representative 'low-output/high-citation' profile. Stephanidis and Constantine (45 citations), along with Fink, Giudice, Crabb, Heron, and others (approximately 36 to 43 citations), form a stable group of authors with three papers who demonstrate strong per-paper impact. Collectively, Baldiris and Sarcar serve as 'high-impact benchmarks,' while the group of three-paper authors exhibits solid single-paper visibility and has the potential to drive thematic development. Meanwhile, several authors with citations of nine or fewer citations are still in the process of accumulating influence, possibly due to the relative recency of their publications and the visibility of the venues in which they were published.

Table 2
High-Impact Author Analysis.

Serial Number	Label	Number of articles	Total citations	H-index
1	baldiris, silvia	5	136	14
2	goodman, Lizbeth	4	23	7
3	ceron, jhoni	3	4	3
4	crabb, Michael	3	40	6
5	fink, paul d. s.	3	43	7
6	giudice, nicholas a.	3	43	21
7	heron, michael	3	39	6
8	keates, simeon	3	5	5
9	laska-lesniewicz, anna	3	6	7
10	martin-gutierrez, Jorge	3	9	20
11	mengoni, maura	3	9	4
12	munteanu, cosmin	3	36	17
13	othman, achraf	3	37	9
14	quintero, Jairo	3	4	3
15	raponi, damiano	3	9	3
16	raposo, rui	3	3	4
17	sarcas, sayan	3	93	12
18	sin, jaisie	3	36	8
19	stephanidis, constantine	3	45	20
20	szentirmai, attila bekkvik	3	4	8
21	vairinhos, mario	3	3	5

3.3 Analysis of Literature Co-Citation

The table below summarizes the top ten core references ranked by co-citation frequency (see Table 3), with all included references having co-citation counts of three or more. Notably, the highest-ranked reference is co-cited only five times, indicating that the field's knowledge base of the field remains dispersed and has yet to develop a highly concentrated pattern. These highly co-cited references collectively delineate four main strands of the field's knowledge base. 1. UDL on the Knowledge Axis: Both CAST (2018 UDL v2.2) and CAST (2024 new edition) rank among the most frequently cited sources, highlighting that the “UDL Guidelines” serve as the primary methodological foundation for accessibility

research in educational settings, consistently used as normative and framework-based references (CAST, 2024; Technology, 2018). 2. HCI Accessibility Interaction as the Second Pillar: Evidence from leading HCI venues, such as Mott (ASSETS 2020), Gerling (CHI 2020), and Zhao (CHI 2019), ranks highly, indicating that interaction design, usability evaluation, and inclusive processes serve as essential engineering and evaluation mechanisms in accessibility research (Kriglstein et al., 2020; Mott et al., 2020; Zhao et al., 2019). 3. The Rise of Evaluation Systems in Educational Technology and AI in Education: Baker (IJAIED 2022) and Bray (BJET 2024) are cited, indicating that the concepts of “learning outcomes, personalization, and ethical governance” have been integrated into a computable chain of evidence (Baker & Hawn, 2022; Bray et al., 2024). This development positions educational technology journals as emerging authoritative sources of support. The interdisciplinary reinforcement of interpretability is exemplified by the works of Quintero (2019) in *Frontiers in Psychology* and Akçayır (2017) in *Educational Research Review*, which together provide both methodological and experiential explanatory power from psychological and review perspectives (Akçayır & Akçayır, 2017; Quintero et al., 2019). This complements existing experimental and applied research. The current knowledge base consists of four interconnected domains: UDL guidelines, HCI accessibility interactions, AI-in-education evaluations, and interpretations based on psychological reviews. However, a significant shortcoming is the scarcity of high-intensity consensus literature. Future research should focus on developing reusable evaluation standards for UDL, XR, and AI, aiming to produce core references and benchmark data that exhibit a stronger ‘anchoring effect’ (Simon-Liedtke & Baraas, 2022). In addition, although Dudley J. (2023, *Virtual Real–London*) is the most highly co-cited reference, it primarily focuses on accessibility-oriented practical validation of XR technologies in educational and rehabilitation settings, representing application-level empirical research. Its contribution to the methodological framework is limited; therefore, it was not included in the main line of research (Dudley et al., 2023).

Table 3
Top 10 co-cited reference.

Rank	Label	Author	Source	Year	Co-citations
1	Dudley J (2023)	Dudley J	VIRTUAL REAL-LONDON	2023	5
2	CAST (2018)	CAST	UNIVERSAL DESIGN FOR LEARNING GUIDELINES VERSION 2.2	2018	4
3	Quintero J (2019)	Quintero J	FRONT PSYCHOL	2019	4
4	CAST (2024)	CAST	UNIVERSAL DESIGN FOR LEARNING	2020	4
5	Mott ME (2020)	Mott ME	22ND INTERNATIONAL ACM SIGACCESS CONFERENCE ON COMPUTERS AND ACCESSIBILITY (ASSETS 20)	2020	4
6	Gerling K (2020)	Gerling K	PROCEEDINGS OF THE 2020 CHI CONFERENCE ON HUMAN FACTORS IN COMPUTING SYSTEMS (CHI20)	2020	4
7	Bray A (2024)	Bray A	BRIT J EDUC TECHNOL	2024	4
8	Zhao YH (2019)	Zhao YH	CHI 2019: PROCEEDINGS OF THE 2019 CHI CONFERENCE ON HUMAN FACTORS IN COMPUTING SYSTEMS	2019	4
9	Akçayir M (2017)	Akçayir M	EDUC RES REV-NETH	2017	3
10	Baker RS (2022)	Baker RS	INT J ARTIF INTELL E	2022	3

3.4 Analysis of Knowledge Flows

The dual-map overlay is a powerful visualization tool for scientific knowledge that integrates CiteSpace layers onto a foundational citation map to intuitively illustrate the interrelationships among journals across various disciplinary fields(Chen, 2013). This method clarifies the connections between citing fields (shown in the left figure) and cited fields (shown in the right figure), thereby revealing the characteristics and patterns of interdisciplinary knowledge flow. By using CiteSpace to perform a dual-map overlay analysis of journal publications, colored paths represent citation relationships, as demonstrated in Fig. 4.

The results indicate that the journals shown on the left side of the figure are the citing journals, primarily concentrated along two active clusters: (1) Psychology–Education–Health and (2) Systems–Computing–Computer. Additionally, there is a minor contribution from the social sciences, including Economics and Political Science. Conversely, the right side features the cited journals, which

predominantly cluster into two groups: (1) Systems–Computing–Mathematics and (2) Health–Nursing–Medicine. Furthermore, these cited journals extend into natural sciences disciplines such as Chemistry, Materials Science, Physics, and Ecology, particularly Plant Sciences. The findings highlight three significant directions of knowledge flow, represented by arrows oriented from left to right: $\rightarrow$ Education, psychology, and health extensively reference algorithms, systems, and data methods derived from the field of computer science (method inputs). $\rightarrow$ Outputs from computer systems significantly influence application domains such as medicine, nursing, and rehabilitation (application landing), while simultaneously establishing a bidirectional coupling with education and psychology—illustrated as 'methods entering scenarios, scenarios feeding back into methods.' $\rightarrow$ Disciplines related to materials and sensing contribute to the hardware and perception layers, encompassing wearables, haptics, and environmental sensing (upstream of methods and devices). These patterns suggest a dual-center configuration of 'computing methods $\leftrightarrow$ education/health scenarios': computer science acts as the primary 'method source,' whereas education and medicine function as the principal 'application sinks'; a stable chain of interdisciplinary knowledge transfer exists between them. Although social sciences are involved, their influence remains comparatively minimal.

3.6 Analysis of International Collaboration

Institutional analysis reveals the distribution patterns of major contributors and collaboration networks within the research field, identifies core institutions and their academic influence, and provides a foundation for decision-making regarding academic resource allocation and scientific research collaboration (Yao et al., 2025). In terms of output scale (see Table 4), the University of Toronto leads with nine papers, followed by Politecnico di Milano and the University of Cambridge, each with seven papers, and University College Dublin with six. Northeastern University, NTNU, the University of Dundee, and the University of Washington each contributed five papers. Notably, the University of Dundee ranks first in impact, with an average of 25 citations per paper (five papers yielding 125 citations). Northeastern University follows with an average of 16 citations per paper (five papers yielding 82 citations), indicating high visibility and strong reusability of its topic selection and collaboration network. The University of Toronto leads with nine publications, maintaining an average of only ten citations per paper. The University of Washington follows with five publications, also averaging ten citations, placing it in the second tier. The University of Cambridge has seven publications with an average of approximately six citations, while University College Dublin has six publications averaging around four citations. Georgia Tech and Lodz each have four publications, with Georgia Tech averaging six citations and Lodz averaging two. Politecnico di Milano has seven publications with an average of approximately 1.4 citations, and NTNU has five publications averaging one citation. This data reflects a typical engineering-method orientation among these institutions, characterized by lower short-term citation rates. Consequently, research directions that are interdisciplinary and closely linked to practical applications are more likely to achieve higher average citations per paper. In contrast, high-output teams focusing on engineering methods tend to experience slower short-term citation returns.

Table 4
Leading institutions by publications and citations (2000–2025).

Serial Number	Institution	Number of articles	Total citations	Average number of applications
1	University of Toronto	9	90	10
2	Politecnico di Milano	7	1	1
3	University of Cambridge	7	40	6
4	University College Dublin	6	25	4
5	Northeastern University	5	82	16
6	Norwegian University of Science and Technology	5	6	1
7	University of Dundee	5	125	25
8	University of Washington	5	50	10
9	Georgia Institute of Technology	4	25	6
10	Lodz University of Technology	4	6	2

To further analyze inter-institutional collaboration, this study employs VOSviewer to characterize research capacity and influence at the institutional level(Savić et al., 2017). Using a sample of 658 institutions, it constructs a co-occurrence map of institutional collaborations in the field of accessible design (see Fig. 5).

Nodes represent institutions, with their size corresponding to publication volume; edges indicate collaborative relationships, and color intensity reflects the strength of collaboration. Overall, the map reveals a distinct structure: a few institutions form a high-density core, while numerous peripheral nodes are weakly connected and exhibit limited collaboration, creating a clear pattern. This suggests that the field is still in a phase of expansion and aggregation. The University of Toronto stands out as the only strong hub, characterized by the largest node and the densest edges, and it also serves as a crucial cross-cluster linking node. Toronto and Aveiro have established a strong bidirectional collaboration axis (indicated by a dark, thick line) and are connected to Tartu and Lodz, forming a stable evaluation network for XR, HCI, and accessibility. Toronto extends its influence to numerous nodes across North America and the Asia-Pacific region, including Michigan, Tsukuba, OCAD, Maryland, Illinois, Washington, and Northeastern. In contrast, Cambridge, Politecnico di Milano, NTNU, and Birmingham City University primarily connect to the core through weaker links (1–2 papers). Cross-regional collaboration is predominantly bilateral, with no significant clusters emerging within the respective regions. Microsoft Research maintains limited and sporadic connections with universities, marked by minimal industry involvement and insufficient depth. The current collaboration network is highly centralized, and the

absence of cross-continental and cross-sector partnerships represents a significant bottleneck. To improve knowledge diffusion and the translation of research outcomes, hubs like Toronto should act as anchors to foster multilateral collaborations with Europe and industry. This approach includes establishing standardized joint projects, such as XR accessibility interfaces and evaluation baselines, while promoting sustained tripartite collaboration among academia, industry, and healthcare(Rawat & Hagos, 2024).

3.6 Analysis of International Collaboration

The analysis of inter-country collaboration offers valuable insights into the global patterns of scientific cooperation. As illustrated in Fig. 6, a total of 69 countries have participated in research on AI-enabled accessible design, revealing a distinct tripolar distribution: North America and Western Europe form the first tier; East Asia and Oceania comprise the second tier; while South America and certain regions of Southern and Northern Europe serve as emerging growth areas.

Among the countries analyzed, the United States leads with 96 published papers, demonstrating a strong capacity for systematic research in areas such as Human-Computer Interaction (HCI), Extended Reality (XR), and accessibility within educational and medical contexts. The United Kingdom follows in second place with 49 papers, benefiting from a well-established policy environment that promotes inclusive design and digital accessibility. Italy (31), Spain (28), and Germany (25) collectively form an active cluster in Western Europe, emphasizing both engineering and interaction. China (29) and Japan (15) contribute significantly at different ends of the spectrum, focusing on computational engineering and its application scenarios. Australia (14) and Canada (20) maintain stable outputs in this field. Norway (18), Ireland (14), Greece (13), and others represent distinctive nodes in Europe, particularly in areas such as rehabilitation engineering, educational accessibility, and XR interfaces. Emerging economies, including India (12), Sweden (12), Brazil (10), and South Korea (10), have entered the forefront, reflecting the global diffusion of this topic. Overall, the landscape has evolved from the dominance of the UK and US to a multi-centered configuration encompassing North America, Western Europe, and East Asia, with the inclusion of peripheral countries primarily linked to XR accessibility, wearable sensing, and applications in education and healthcare.

By combining the spatial clustering shown on the world map with the proportions illustrated in the ring chart, several key observations emerge. First, the English-language scholarly community—including the United States, the United Kingdom, Canada, and Ireland—remains central in terms of both quantity and impact. Second, countries with strong engineering and interaction capabilities, such as Italy, Spain, Germany, and Japan, consistently produce stable outputs in XR, wearables, and evaluation methods. Third, the emerging belt, which includes India, Brazil, South Korea, and the Netherlands, though currently small in scale, is experiencing rapid growth and offers opportunities for cross-regional method sharing and scenario validation. For future research, it is advisable to align the methodological and data resources of North America and Western Europe with the application scenarios and engineering capabilities of East Asia and Oceania. This alignment should prioritize multilateral collaboration on XR accessibility interfaces, including captioning, sign language, haptics, and spatial orientation(Fox &

Thornton, 2022; Rakkolainen et al., 2021). Additionally, it is essential to simultaneously release standardized assessments and open benchmarks to enhance cross-national reusability and citation impact.

3.8 Keyword Clustering Analysis

To identify research themes and hotspots and to elucidate the core structure of the field, this paper performs clustering and distillation on the keyword co-occurrence map, as shown in the figure.7. The size of each node reflects term frequency and intensity, while distinct colors denote different clusters. The dense cross-cluster connections indicate strong co-occurrence among themes and a high degree of knowledge coupling(Xue & Cui, 2024). The network is clearly segmented into five functional clusters, forming a five-ring structure: "UDL (educational paradigm) – UCD (interaction methods) – XR (technical medium) – Inclusive Design (scenario-based applications) – Governance (regulatory norms)." Cluster #3 (XR) serves as the linking center; clusters #1 and #4 represent the primary application fronts; cluster #2 provides methodological support; and cluster #5 constitutes the normative and oversight framework.

Cluster #1 (Educational Accessibility: UDL and Classroom Practice): This cluster focuses on Universal Design for Learning (UDL) and includes topics such as students, serious games, instructional methods, educational technology, and augmented reality(Gill et al., 2024; Zaugg, 2024). It emphasizes curriculum design, instructional evaluation, and classroom support with UDL at its core. The strong co-occurrence of UDL with augmented reality, gaming, and experiential learning indicates that integrating "UDL × XR/gamification" is becoming a key approach to enhancing learning motivation and accessibility.

Cluster #2 (User-Centered Accessible Interaction): This cluster centers on web accessibility, user-centered design, user experience, participatory design, ergonomics, smart home technology, and the digital divide(Choi & Chang, 2025; Wei & Margetis; Zaugg, 2024). It forms a continuous chain of "participatory design—experience evaluation—home and IoT scenarios.

Cluster #3 (XR Technologies and Vision-Oriented Accessibility Engineering): Focused on virtual and augmented reality, this cluster addresses vision and visual impairments, perception, assistive technology, autonomous vehicles, and accessibility(Peltonen et al., 2020). It serves as a technical hub bridging education and engineering and is closely connected with Clusters #1 and #4, highlighting the widespread application of XR in educational accessibility and universal/inclusive design.

Cluster #4 (Inclusive Design and Scenario-Based Applications): This cluster encompasses inclusive design, human-computer interaction, smart cities, digital twins, autism, and special educational needs(Abdelsalam et al., 2025; Abiodun et al., 2024; Lin et al., 2025). It emphasizes scenario-based implementation and personalized support across educational, urban, and rehabilitation contexts. It demonstrates strong connections with XR, HCI, and evaluation metrics.

Cluster #5 (Governance and Norms: Rights, Privacy, and Guidelines): This cluster includes universal design, inclusion, rights, privacy, guidelines, and communication(Hofmann & Pawlak, 2023; Riedmann-

Streitz et al., 2025; Steinfeld & Maisel, 2012; Stienstra, 2006). It highlights the growing importance of rights protection, privacy compliance, and standard-setting in recent years. Together with the other clusters, it completes the full cycle of "design—implementation—evaluation—governance."

Overall, the five clusters illustrated in the figure correspond to the division of labor and the interconnection among "methods, media, applications, and governance." Extended Reality (XR) serves as the technical hub, while Universal Design for Learning (UDL) and inclusive design form the core of the applications (Kim & Ryu, 2024; Videla et al., 2025; Zaugg, 2024). User-Centered Design (UCD) and User Experience (UX) provide essential process levers, and the governance cluster ensures compliance and extensibility (Lemola, 2024; Schwoerer). Future emphasis should be placed on integrating UDL, Artificial Intelligence (AI), and XR, as well as achieving cross-scenario consistency and conducting upfront evaluation and governance.

3.9 Keyword Trend Analysis

The keyword trend chart displays years along the horizontal axis and thematic terms along the vertical axis. Line segments indicate active intervals, while the size of the bubbles represents term frequency (Kontostathis et al., 2004). This visualization effectively illustrates the phased evolution of attention and thematic shifts in accessible design from 2009 to 2025. As shown in Fig. 8, the overall pattern reveals a three-stage configuration.

Foundation Period (circa 2016): The fields of human-computer interaction, inclusive design, and haptics/mixed reality established a foundational framework for general accessibility and early interaction media (Bianchi et al., 2023; Pogmore et al., 2024). **Transition Period (2017–2020):** Concepts such as universal design, rehabilitation, evaluation, participatory design, and considerations for children developed alongside augmented and virtual reality (Creed et al., 2024; Dudley et al., 2023), fostering a synergistic relationship between these ideas and the three application domains of education, rehabilitation, and evaluation, which began integrating with XR technologies. **Accelerated Integration Period (2021–2025):** Emphasis on artificial intelligence, inclusive design, accessibility, user experience, and autism has significantly increased (Chandramma et al., 2025; El Morr et al., 2024). Additionally, universal design for learning (UDL) and digital literacy have remained prominent, indicating that educational paradigms and methodological frameworks have evolved to become the dominant influences (Puerto & Gutiérrez-Esteban, 2022).

Approximately two-thirds of the topics emerged after 2017, with hotspots primarily concentrated in the past decade. Human-computer interaction and design for all have remained consistent themes throughout this period. In 2017, the concept of reached a significant peak (approximately 40), while in 2019, interaction design achieved an even higher peak (approximately 60). Notably, in 2020, inclusive design and its impact on people manifested as (approximately 80). From 2021 to 2023, the focus on AI, UX, and accessibility intensified. Additionally, UDL and digital literacy have experienced rapid growth since 2022. The active intervals for XR (VR, AR, mixed reality, haptics) predominantly span from 2016 to 2023, showing substantial overlap with assistive technology and evaluation. This indicates the

emergence of a stable triadic combination: XR as the medium, AI as the capability, and UDL as the paradigm. Concurrently, research on autism and children, along with evaluation, has strengthened, shifting the focus from to verifiable evidence concerning population specificity and learning outcomes(Travers & Ayres, 2015). Consequently, three high-potential pathways can be prioritized: standards and interoperability for XR accessibility interfaces (including captioning, sign language, haptics, and spatial orientation); a transferable framework for AI personalization and contextual adaptation within UDL; and fairness- and explainability-oriented evaluation across populations, supported by real-world longitudinal evidence(Gao et al., 2025).

3.10 Analysis of Keyword Burst Intensity

To reveal the evolution of hotspots and frontier trends in 'AI-enabled accessible design,' this paper constructs a keyword co-occurrence map and identifies the top 30 emerging terms (see Fig. 9). Overall, it outlines a three-stage trajectory: conceptual grounding, scenario penetration, and paradigm integration.

Stage 1: Early Groundwork (2019)During this period, burst terms are predominantly short-lived, including those from 2016, 2017, and the concept of universal design introduced in 2019. These terms focus on defining target groups and establishing the framework for universal design, thereby laying the foundational discourse and value framework for the field.

Stage 2: Scenario Penetration (2020–2021)This stage closely aligns with the pandemic period. Terms such as communication (2019–2021), conversational user interfaces (2020), virtual assistants (2020–2021), and visual impairment (2020) experienced rapid growth. This growth indicates the accelerated deployment of AI solutions—such as natural language processing, speech interaction, and virtual assistants—in educational and rehabilitation contexts.

Stage 3: Paradigm Integration (2022–2025)A structural clustering of "XR × AI × education" emerges during this phase. Concepts such as universal design for learning, augmented reality, higher education, care, human–computer interaction, and user experience (2012–2025) exhibit sustained strong bursts. Additionally, challenges identified from 2022 to 2025 show the highest intensity, signaling that evaluation, ethics, and scalability have become central concerns.

To avoid overgeneralization, the results are divided into two categories: those still in the burst period and those whose burst has ended. The categories remaining in the burst period, extending to 2025 and roughly ordered by intensity, include technology, framework, usability, and challenges (2022/2024–2025). This suggests a transition from "can be built" to "how to standardize the process and measure it," with evaluation and governance taking precedence. In higher education, areas such as students and inclusive education (2022/2023–2025) indicate that the educational landscape is the most stable, with learners and campus applications continuing to gain momentum. User experience (2023–2025) demonstrates that experience has become a core evaluation dimension, linked to quantitative indicators such as usability and load. Meanwhile, generative AI, immersive technology, systems, and meta-analysis (2024–2025) highlight the emergence of engineering integration of generative and multimodal AI with

XR, as well as the importance of evidence synthesis through meta-analysis. In contrast, categories whose burst has ended—representing "high completion or entry into normalization inclusive design and universal design for learning (2021–2022). This indicates a shift from "frontier" to foundational paradigms that continue to influence subsequent work. Augmented reality (2021) and earlier communication, voice, and visual impairment technologies are no longer categorized as separate bursts, as they have been integrated into "immersive technology/XR composite interfaces" and broader application frameworks.

As of 2023, Human-Computer Interaction (HCI) research involving older adults has reached a mature phase of application and evaluation. This should not be mistaken for a decline in interest or relevance. Projections for 2024 suggest that advances in generative AI, immersive technology, and meta-analysis will reveal two significant trends. First, generative and multimodal AI are evolving from mere feasibility demonstrations to rigorous usability and fairness validations within accessibility contexts (Kolhatin, 2025; Srinivasa Rao et al., 2025). Second, there is a growing methodological emphasis on evidence synthesis and quantitative reviews. Concurrently, persistent high-frequency terms such as and have endured from earlier periods to the present, indicating that the foundational relationship among methods, systems, and usability remains strong. Furthermore, the sustained focus on older adults from 2014 to 2025, alongside inclusive education, underscores the ongoing demand in aging and educational contexts.

Accordingly, three actionable pathways can be prioritized: (1) Paradigm Building for Generative and Multimodal AI: This involves developing a transferable framework that integrates generative AI, inclusive design, Universal Design for Learning (UDL), and user experience to support teaching and rehabilitation (Black, 2024; Zaugg, 2024). It is essential to establish a closed evidence loop incorporating meta-analyses, usability studies, and frameworks to shift the focus from solely technological innovation to emphasizing usability and trustworthy governance. (2) Standardization and Interoperability of XR Interaction Interfaces: This pathway aims to anchor the rapid advancements in augmented and immersive technologies, Human-Computer Interaction (HCI), and related challenges in care (Li, 2025; Stanney et al., 2024). It promotes the establishment of cross-platform interface standards and automated testing systems for captioning, gesture recognition, haptics, and spatial orientation (Eswaran & Eswaran, 2025). This will lower engineering integration thresholds and enhance the reusability of these technologies. (3) Fairness and Long-Term Empirical Orientation: For sustained topics such as older adults, individuals with disabilities, higher education, and caregiving, it is crucial to conduct medium- to long-term longitudinal studies (≥ 6 –12 months) in real-world settings (Hill et al., 2016; van der Weegen et al., 2024). These studies should incorporate metrics of fairness, explainability, and adaptability, addressing the current evidence gap caused by short research cycles and single-point validation. The alignment of these pathways with the timing and intensity of technological advancements confirms that the field is progressing from isolated innovations to a stage characterized by integration and standardized evaluation.

4. Discussion

4.1 Overall Findings and Knowledge Graph

Using retrievals from the Web of Science Core Collection spanning 2000 to 2025 as the sample, this study conducts a precise thematic search on "artificial intelligence × accessible design," ultimately including 424 relevant articles. It employs an integrated bibliometric and knowledge-graph approach to systematically depict scale dynamics, thematic hotspots, frontier bursts, and collaboration patterns. The study aims to address Research Questions 1 to 4 (RQ1–RQ4): delineating scale dynamics and stage evolution; identifying collaboration structures among authors, institutions, and countries; distilling thematic backbones and the knowledge base; tracking frontiers and potential shifts; and, based on these findings, constructing a conceptual knowledge graph of "AI-enabled accessible design." The results indicate that:

Scale dynamics continue to accelerate. The period from 2000 to 2015 marked a slow start; from 2016 to 2019, there was a transition into a growth phase; and from 2020 to 2025, high-level activity has emerged, characterized by multi-scenario expansion. This presents a three-stage trajectory of "exploration → coupling → integration." The thematic structure has evolved into a five-layer backbone, comprising "technology empowerment—methodological paradigms—scenario deployment—evaluation and governance—value guidance." The collaboration pattern features a "strong-center–long-tail" dual-hub structure, characterized by dual-center interaction between computer/systems disciplines and education/health disciplines, with several bridging nodes facilitating cross-domain knowledge flows. Knowledge base chains are centered on four key areas: UDL guidelines and classroom practice; HCI and accessibility interaction norms; evaluation systems for AI in education; and evidence drawn from psychological and methodological reviews.

The forefront of research focuses on several key areas: (1) the systematic integration of Universal Design for Learning (UDL), Artificial Intelligence (AI), and Extended Reality (XR), emphasizing the close alignment of goals, representation, and action/expression with personalization and contextual adaptation(O'Rourke & Bobal, 2024; Rocca, 2025; Zaugg, 2024); (2) the standardization and interoperability of XR accessibility interfaces(Makamara & Adolph, 2022), including unified APIs and automated consistency testing for captioning, sign language/gesture recognition, haptics, and spatial orientation(Henlein et al., 2024); (3) the provision of on-demand content and semantic translation through generative and multimodal AI, advancing from feasibility demonstrations to usability and fairness validation(Rabbani et al., 2025; Topalli & Badii, 2025); (4) the evolution of evaluation paradigms alongside evidence synthesis, shifting focus from technical effectiveness to quantitative metrics centered on user experience (UX), usability, cognitive load, and task completion, while establishing comparable baselines through meta-analysis(Ntoa et al., 2021); (5) the establishment of trustworthy governance, involving quantifiable compliance with principles of fairness, privacy, explainability, and cost-effectiveness, thereby promoting cross-platform interoperability and scalable deployment(Hammad & Abu-Zaid, 2024; Stan et al., 2025); and (6) deployment across diverse scenarios and populations, addressing ongoing needs in higher and special education, rehabilitation healthcare, smart homes and cities, as well as among aging and neurodiverse groups(Chrysikou et al., 2024).

Based on the findings presented above, this paper constructs and visualizes a knowledge-structure map (see Fig. 10). It establishes a comprehensive 'UST × lifecycle' coordinate system, with "User–Scenario–Technology" as the horizontal axis and "Needs–Design–Deployment–Evaluation–Governance" as the vertical axis. This system is used to identify primary pathways, break zones, and transfer conditions. The central layer illustrates technology modules, including AI, XR, immersion, and multimodal sensing. The methods layer anchors UDL, Inclusive Design, UCD co-creation, and HCI. The application layer encompasses education, rehabilitation, home, and urban contexts. The evaluation and governance layer is constrained by factors such as usability, fairness, privacy, explainability, and standards (e.g., WCAG, ISO, IEC)(Islam et al., 2025; ZHOU, 2025). The outermost value layer provides directional constraints through accessibility, inclusion, user experience (UX), and equity(Bakhshandeh, 2025; Ghosh & Dubey, 2025). This map clearly illustrates the closed loop from "technical capability" to "methodological paradigm," followed by "scenario-based implementation," "evidenced evaluation and compliant governance," and ultimately leading to "value realization." It grounds the "frontier focus" in three executable main lines: UDL × AI × XR integrated course/rehabilitation support; standardization and automated evaluation of XR accessibility interfaces; and long-term real-world evidence centered on fairness and explainability(Ghosh & Dubey, 2025; Sistemico & Di Salvo).

4.2 Future Promising Technological Directions

Synthesizing publication trends, keyword clustering, burst terms, and the "UST × lifecycle" map for the 2000–2025 period, the future application of AI in accessible design is expected to advance along the triadic backbone of "XR media—Inclusive/UDL paradigms—interaction evaluation." This evolution will exhibit strong momentum and practical deployability across several directions. First, generative and multimodal models (text, image, audio, video) will serve as the core engine for content personalization, directly supporting automatic captioning, audio description, sign language and gesture synthesis, scene summarization, and the rewriting of learning materials—thereby transitioning from "assistive tools" to "content producers"(Heilala et al., 2025; Kaur et al., 2025) .Second, real-time semantic understanding and intent recognition, leveraging ASR, NLP, and large models, will facilitate the widespread adoption of conversational accessibility assistants in classrooms, clinics, and government services, encompassing spoken language, dialects, and noisy environments(Habeeb & Budd, 2025; Pashangpour & Nejat, 2024). Third, cross-modal alignment and interpretability across vision, language, and audio will provide equivalent information access for individuals with visual impairments and reading difficulties (e.g., image captioning, screen-reading explanations, environment and emotion recognition), thereby enhancing scene understanding and task completion(Ai & Fang, 2023). Fourth, XR accessibility interfaces (VR/AR/MR) will evolve from disparate prototypes to engineering standardization: unified APIs and automated consistency testing (MVT) will be established for captioning, sign language and gestures, haptics, spatial audio, and orientation—thus supporting scaled deployment through cross-platform interoperability(Ilievska, 2025; Prianka et al., 2024). Fifth, personalization and contextual adaptation (ability profiling and context sensing), oriented toward the UDL "triadic structure" (goals, representation, expression), will emerge as the key mechanism for instructional and rehabilitation adaptation, enabling on-demand composition and load scheduling. Sixth, edge AI and wearable sensing

enable on-device inference in devices such as hearing aids, haptic feedback systems, navigation glasses, and canes(Sharma et al., 2025; X. Wang et al., 2025; Wazirali et al., 2025). This capability reduces latency and dependence on network connectivity while enhancing offline availability and privacy protection. Seventh, privacy-preserving and compliant data intelligence techniques—including federated learning, differential privacy, and data contracts—provide auditable data flows for cross-institutional collaboration and multi-center studies(Chadha, 2024; Kumar et al., 2025). These methods help overcome sensitivity and data-sharing barriers associated with vulnerable populations. Eighth, digital twins and accessibility simulation/path planning facilitate pre-deployment verification and in-operation optimization of accessibility layouts in campuses, hospitals, and urban spaces, thereby reducing retrofit costs. Finally, in high-risk contexts such as educational interventions and medical rehabilitation, explainable AI supports human–AI co-decision-making through uncertainty prompts and causal cues, enhancing trust and adoption among professionals and users(Havely, 2004).

To ensure the reusability and evaluability of the implementation of the above directions, we recommend adopting the "UST × lifecycle (User–Scenario–Technology × needs–design–deployment–evaluation–governance) as a unified coordinate system at the implementation level. This approach involves completing ability profiling and interface selection during the needs–design phase, implementing unified APIs and automated consistency testing in the deployment phase, and establishing indicators and reporting specifications in the evaluation and governance phases based on a three-layer evidence stack of "technology–experience–governance." Furthermore, on the data front, we advocate achieving cross-institutional compliant circulation through federated learning, privacy-preserving computation, and data contracts(Manwani; Melo, 2025; Y. Wang et al., 2025). This pathway effectively links "model capabilities, interface standards, and evidence closed loop," facilitating a transition from "compensatory tools" to a "co-creative ecosystem." Ultimately, this framework provides operational technical levers and evaluation bases essential for policymaking and industrialization.

4.3 Explanation of Mechanisms and Real-World Implications

Methods Layer: Integration Mechanisms of UDL, AI, and XR

Analysis of keyword co-occurrence and burst patterns clearly indicates that the integration of "UDL × AI × XR" has become the dominant research focus in this field. This convergence is not coincidental; rather, it reflects a natural alignment between methodological principles and technological capabilities. The "triadic structure" of UDL (goals–representation–expression) provides a foundational framework for personalized and inclusive instruction. Concurrently, generative and multimodal AI can create differentiated learning content—such as text, speech, images, and gestures—within this framework, automatically adapting it to learners' individual characteristics(Jiang & Lai, 2025; Kaur et al., 2025). Additionally, XR technologies (VR/AR/MR) offer immersive, multisensory interactive environments that facilitate the presentation of AI-generated content in a perceivable and engaging manner(Allison et al., 2025; Tabassum et al., 2025; Uddin et al., 2023). When combined with user research, prototyping, and

usability evaluation methods from HCI and UCD, the components of "algorithmic capabilities—interaction media—pedagogical design" achieve systemic integration. This methodological convergence shifts research from "single-technology innovation" toward "holistic instructional and experiential system design," thereby enhancing the usability of AI technologies in education and rehabilitation.

Application Layer: Priority Translational Scenarios and Standardization Pathways

From the clustering and emergent hotspot themes, the scenarios in which AI-enabled accessible design is most likely to be implemented include higher education, special education, rehabilitation, nursing, and continuous accessibility systems spanning home and city environments(Bekbolatova et al., 2024; Malviya & Rajput, 2025). In the educational domain, existing Universal Design for Learning (UDL) curriculum frameworks and evaluation systems offer direct integration points for AI- and XR-enhanced instruction(Barbu et al., 2025). In rehabilitation settings, individualized profiling and the reuse of training pathways can facilitate precise interventions and adaptive training. Furthermore, smart homes and smart cities, leveraging Digital Twin technology, can create consistent, cross-space accessibility experiences(Gautam et al., 2025). To transition from 'point innovations' to 'system-level implementation,' interface standardization is essential. Currently, four categories of XR accessibility capabilities—captioning and audio description, sign language and gestures, haptic feedback, and spatial orientation—urgently require unified API standards, the establishment of reference implementations, automated consistency testing systems, and the release of a Minimum Viable Test set (MVT). These measures will reduce cross-platform interoperability costs and enable XR capabilities to form a genuinely reusable engineering ecosystem.

Governance Layer: Essential Conditions and Mechanism Design for Trustworthy Implementation

Since 2022, fairness, privacy protection, explainability, and cost control have become prominent topics in both research and practice. This trend is driven by policies and international standards, such as the WCAG and ISO/IEC accessibility and interoperability specifications, as well as practical requirements for the sustainable and trustworthy operation of AI systems in cross-platform deployment and large-scale applications(Stout, 2012; Villegas-Ch et al., 2024). Central to achieving this shift is the establishment of a three-layer chain of evidence encompassing technology, experience, and governance. The technology layer emphasizes model accuracy, response latency, and robustness; the experience layer quantifies user experience through metrics such as the System Usability Scale (SUS), Task Load Index (TLX), task completion rate, adherence, and workload levels; and the governance layer integrates indicators including fairness disparities, privacy risks, explainability coverage, and life-cycle costs to create a quantifiable evaluation and accountability system(De Santis & Esposito, 2025; Kemmerzell et al., 2025). Concurrently, at the data level, a compliant collaboration mechanism combining federated learning, privacy-preserving computation, and data contracts should be implemented to facilitate secure sharing and traceable use across institutions. At the governance level, mechanisms for bias auditing, model watermarking, and incident rollback should be established to ensure operational safety and accountability. Through these measures, a closed-loop transition can be achieved from being usable and

trustworthy, thereby driving continuous optimization and scaled application within the UST × lifecycle framework.

4.4 Research Limitations

However, this study is limited by its reliance on a relatively narrow data source, primarily the Web of Science Core Collection for literature retrieval. This dependence may exclude high-quality literature available in certain regional or specialized databases. Such limitations could affect the comprehensiveness of the results, introducing risks related to database coverage, disciplinary bias, and the omission of cross-domain terminology. Consequently, our conclusions are best suited for structural assessments of scale dynamics, collaboration patterns, and thematic trajectories, rather than for extrapolating intervention effectiveness or causal mechanisms. For future research, we plan to supplement our analysis with multiple databases, including Scopus, Dimensions, IEEE Xplore, and CNKI. We will perform robustness tests using union and intersection approaches and incorporate document types in a stratified manner, such as Reviews and Early Access articles, to ensure comparability through grouped specifications.

5. Conclusions

Based on the 2000–2025 WoS Core Collection sample, this paper employs an integrated approach encompassing performance analysis, scientific knowledge mapping, and burst detection, yielding three types of evidence: a structural map of the field, main paths, and frontier identification. The combined results indicate that: (1) current research has established a comprising XR media, inclusive/UDL paradigms, and interaction evaluation (UX/HCI/Assistive Technology), which propels the field from engineering feasibility toward practical application (Alnagrat et al., 2022); (2) the frontier is rapidly shifting toward the deep integration of generative and multimodal AI with UDL, the standardization and interoperability of XR accessibility interfaces, and evidence synthesis/meta-analysis, reflecting a paradigm shift from usability and trustworthy governance; (3) the collaboration ecosystem exhibits a core-periphery structure, wherein a limited number of institutions and countries combine high output with bridging roles, while fault lines persist in cross-continental, academia-industry-healthcare, and cross-disciplinary collaboration.

In terms of application and policy implications, a unified UST × lifecycle coordinate system should first be established to enable research and implementation teams to perform cross-scenario alignment (User–Scenario–Technology) and transition interpretation (needs–design–deployment–evaluation–governance). This system will facilitate the creation of reusable thematic codes and crosswalks for solution selection and replication reporting. Second, a three-layer evidence stack comprising "technology–experience–governance" should be developed, with researchers and evaluation agencies implementing unified metrics and reporting standards. The technology layer will include metrics such as accuracy, latency, robustness, and energy efficiency; the experience layer will encompass measures like

the System Usability Scale (SUS), Task Load Index (TLX), workload, task completion rate, and retention (Alabbas & Alomar, 2025; Zaheer); and the governance layer will address fairness disparities, privacy risks, explainability coverage, operational costs, and standards compliance. This structure aims to produce comparable evaluation dossiers and decision-making foundations. Finally, the standardization and compliance of interfaces and data should be prioritized. Engineering and regulatory bodies should collaboratively adopt unified APIs and automated consistency testing to reduce cross-platform interoperability costs. On the data side, federated learning, combined with privacy-preserving computation and data contracts, should be employed to enable compliant data circulation across institutions, resulting in traceable data assets and audit logs.

Looking ahead to future research, it is advisable to adopt standardized XR accessibility interfaces and to release a Minimum Viable Test set (MVT) that prioritizes coverage of captioning, sign language and gestures, haptics, and spatial orientation. This approach will establish reference implementations and consistency benchmarks. Additionally, it is essential to conduct multi-center, real-world evaluations encompassing the entire lifecycle in higher education, rehabilitation, and urban accessibility scenarios, with ongoing observation and public reporting in accordance with the three-layer evidence stack. Regarding the auditing of deployment bias and incident rollback mechanisms, platform-based operations should institutionalize model bias monitoring, watermark traceability, and version rollback to enhance the safety boundaries and accountability of the research-to-deployment pipeline.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors have no employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, grants or other funding, or institutional affiliations that may be considered as potential competing interests. All authors declare no conflicts of interest relevant to this manuscript.

Author Contribution

Yuang: Conceptualization, Methodology, Validation, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization. Yunqing: Conceptualization, Methodology, Supervision, Project Administration, Writing – Original Draft, Writing – Review & Editing.

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Figures

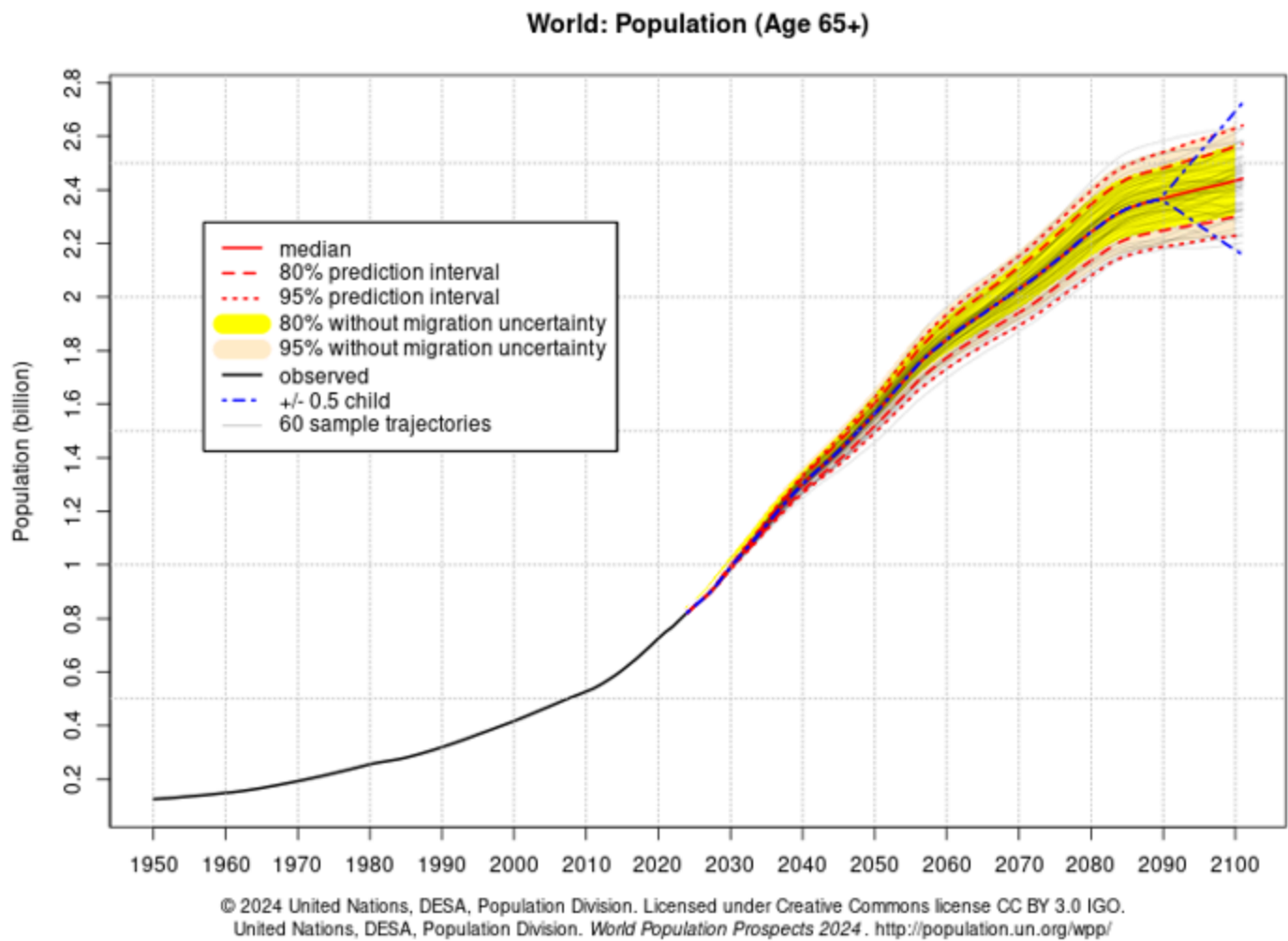


Figure 1

Global populations of older adults and persons with disabilities, and trends (2000–2050).

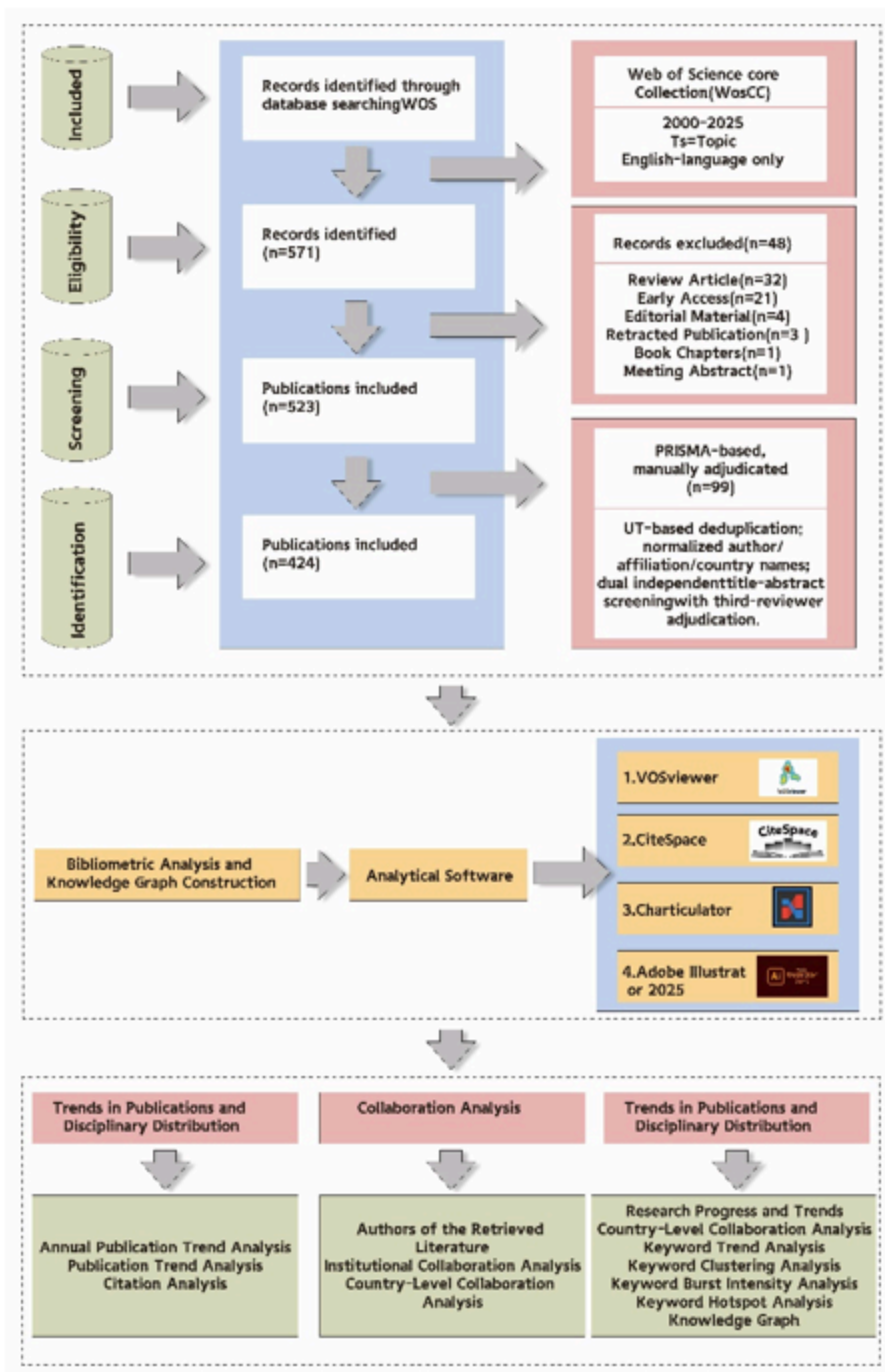


Figure 2

Data Retrieval Flowchart.

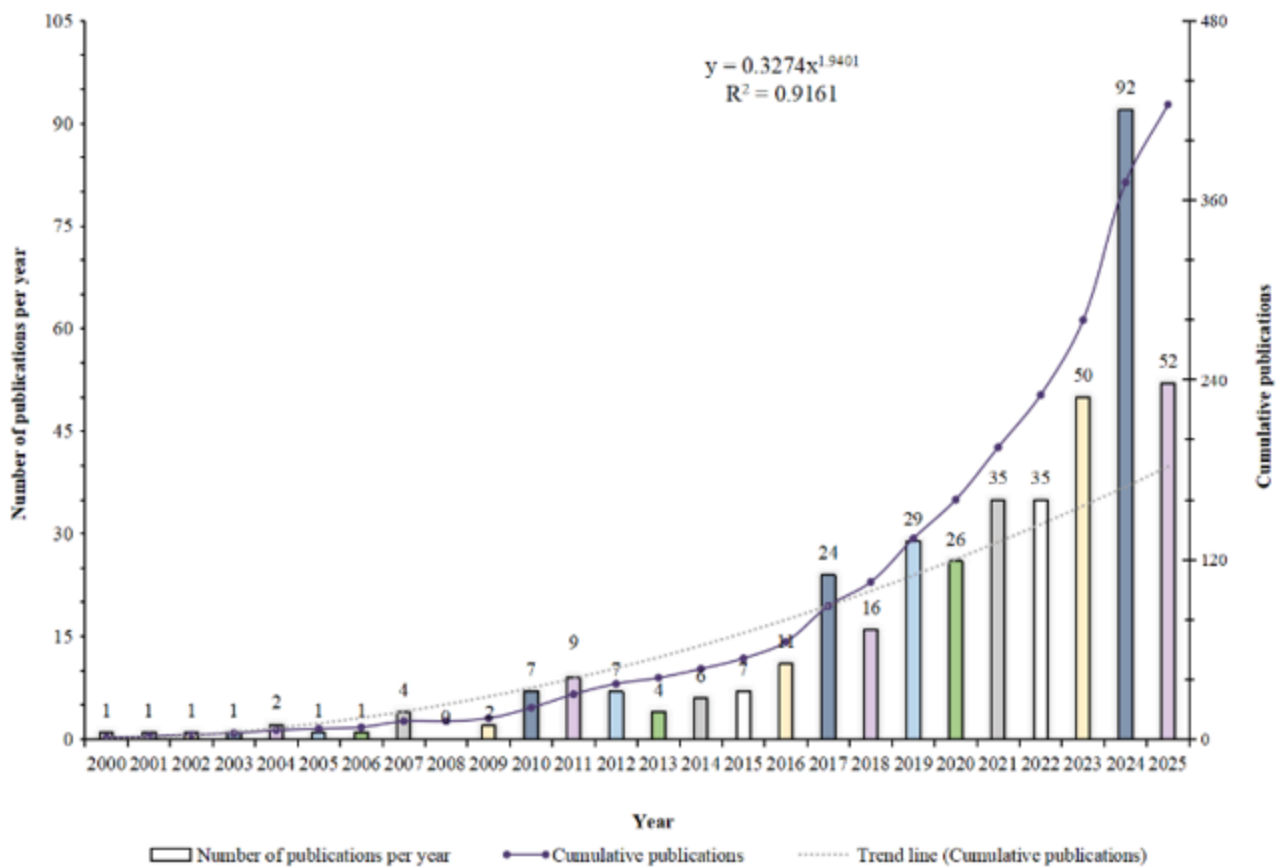


Figure 3

Annual and cumulative publications on AI-enabled accessible.

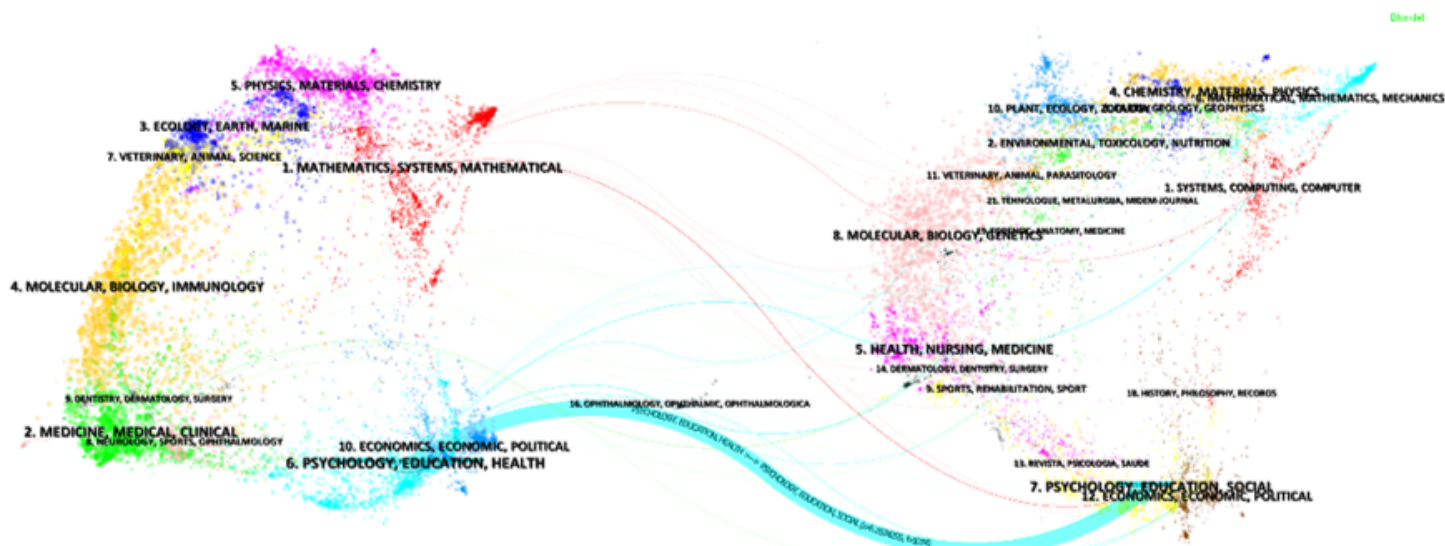


Figure 4

Journal overlay map of AI-enabled accessible design (2000–2025).

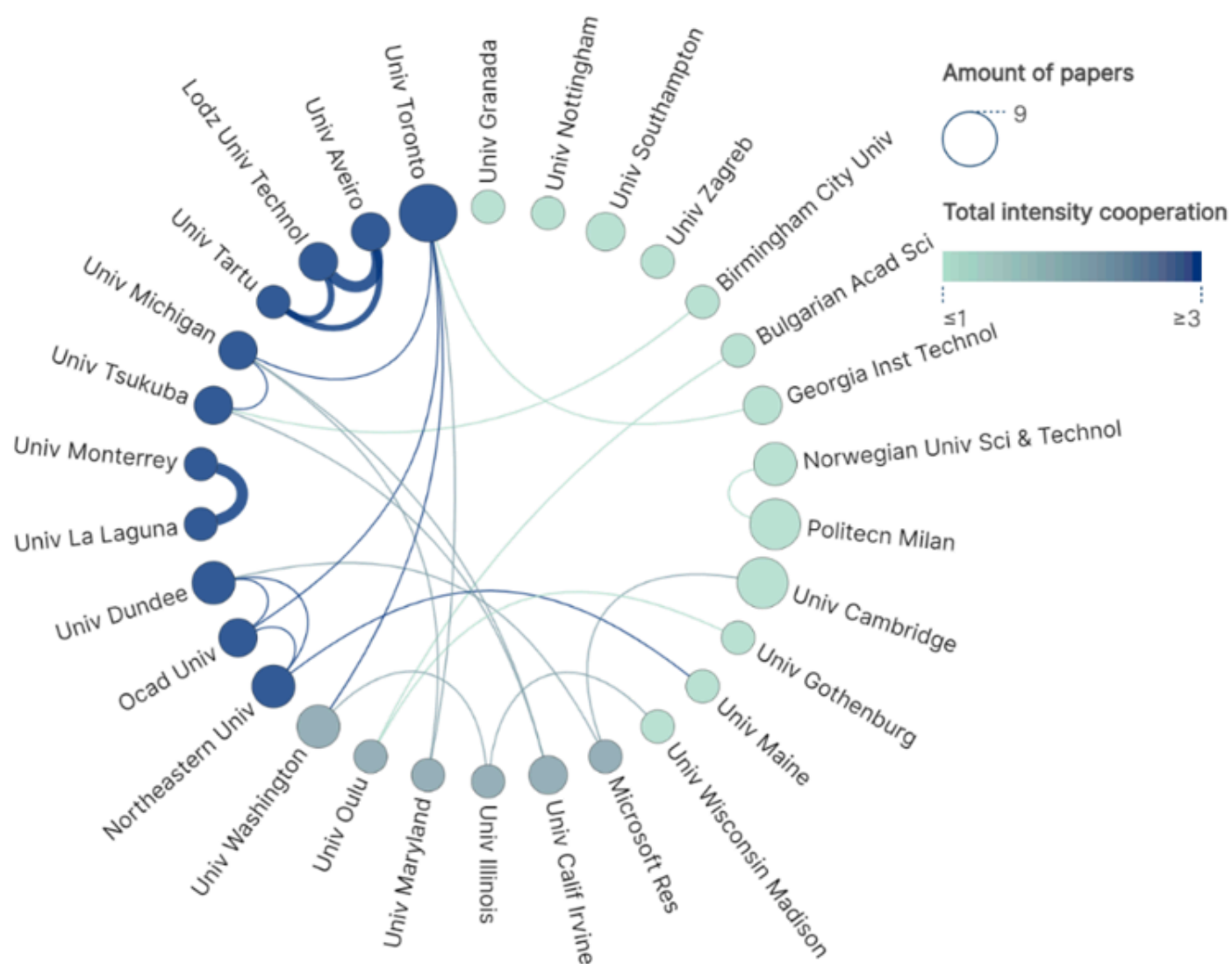


Figure 5
Inter-institutional collaboration network (2000–2025).

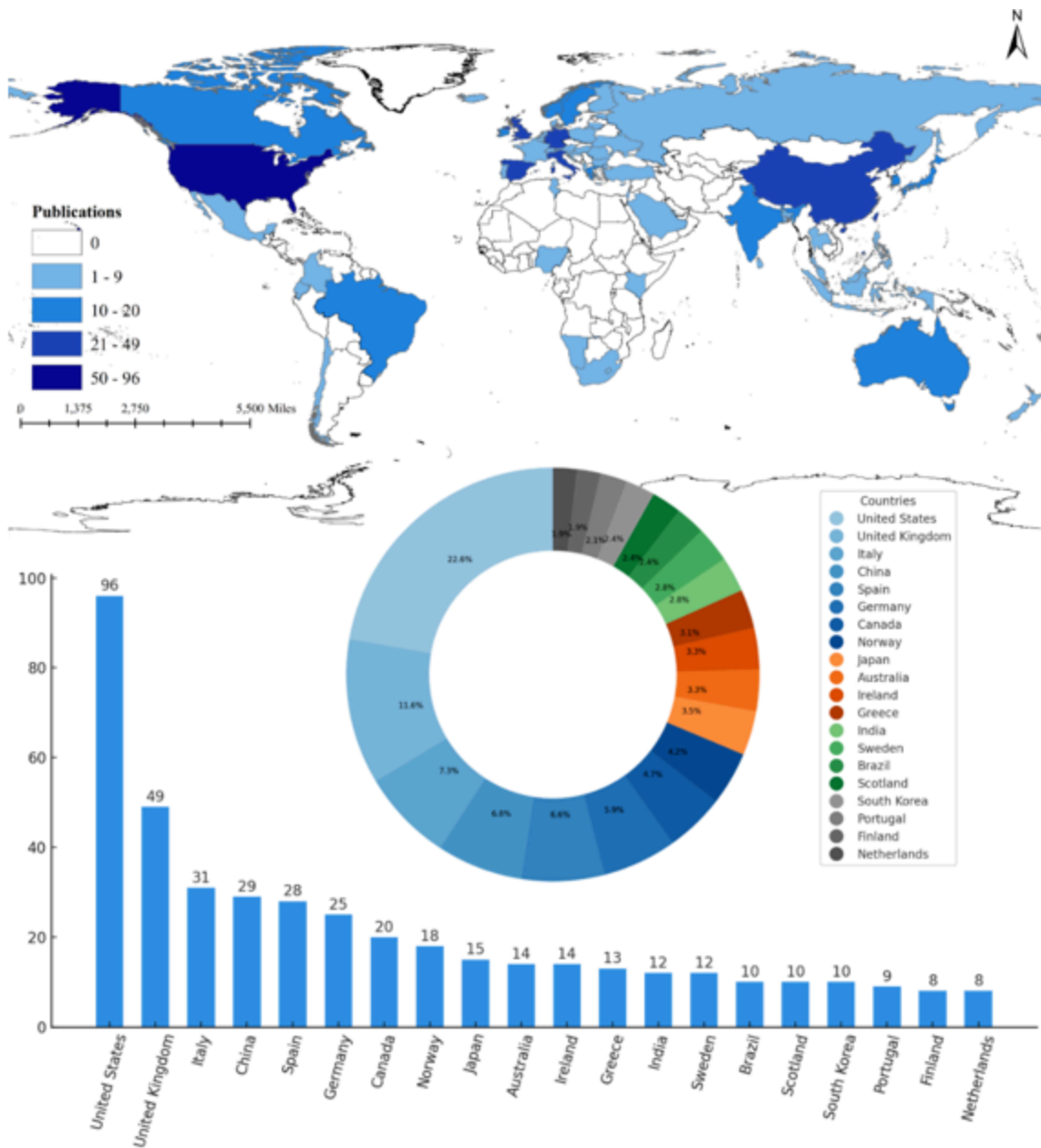


Figure 6

Global distribution of publications by country in AI-enabled accessible design.

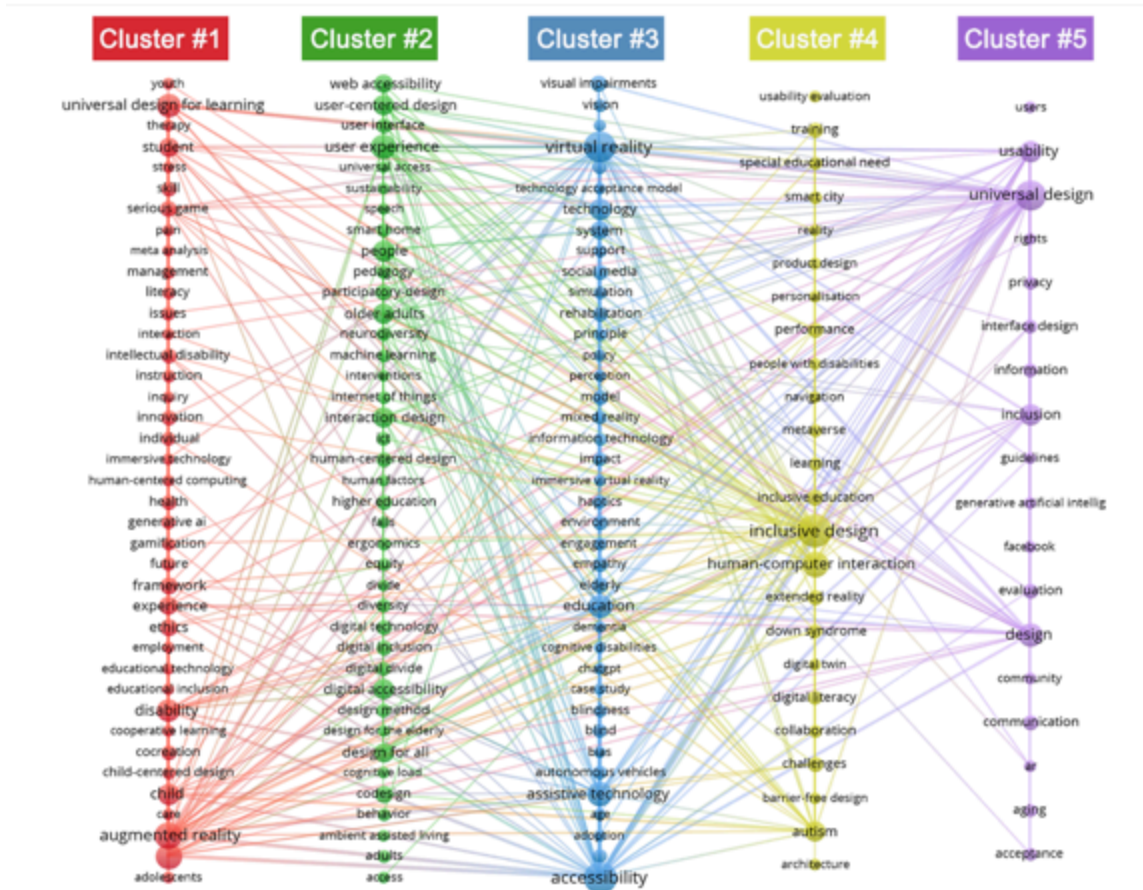


Figure 7

Keyword co-occurrence clustering in AI-enabled accessible design.

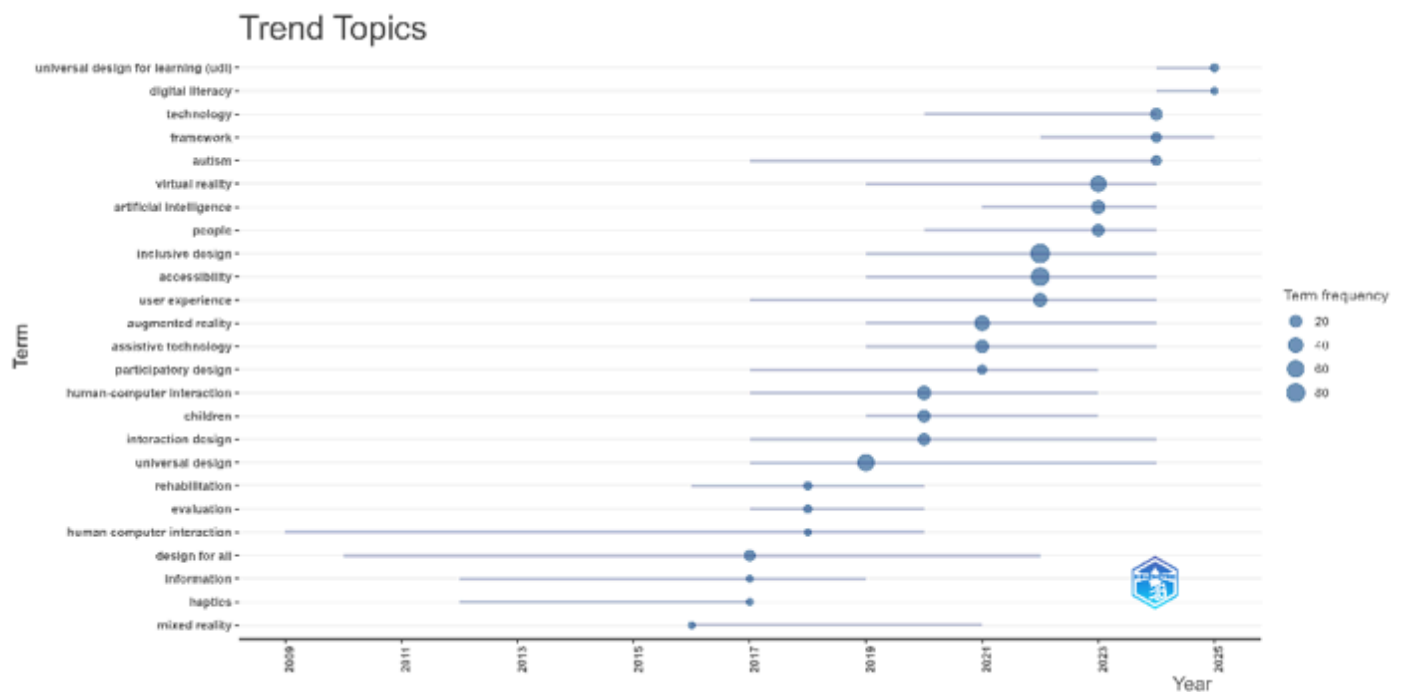


Figure 8

Trend topics timeline in AI-enabled accessible design.

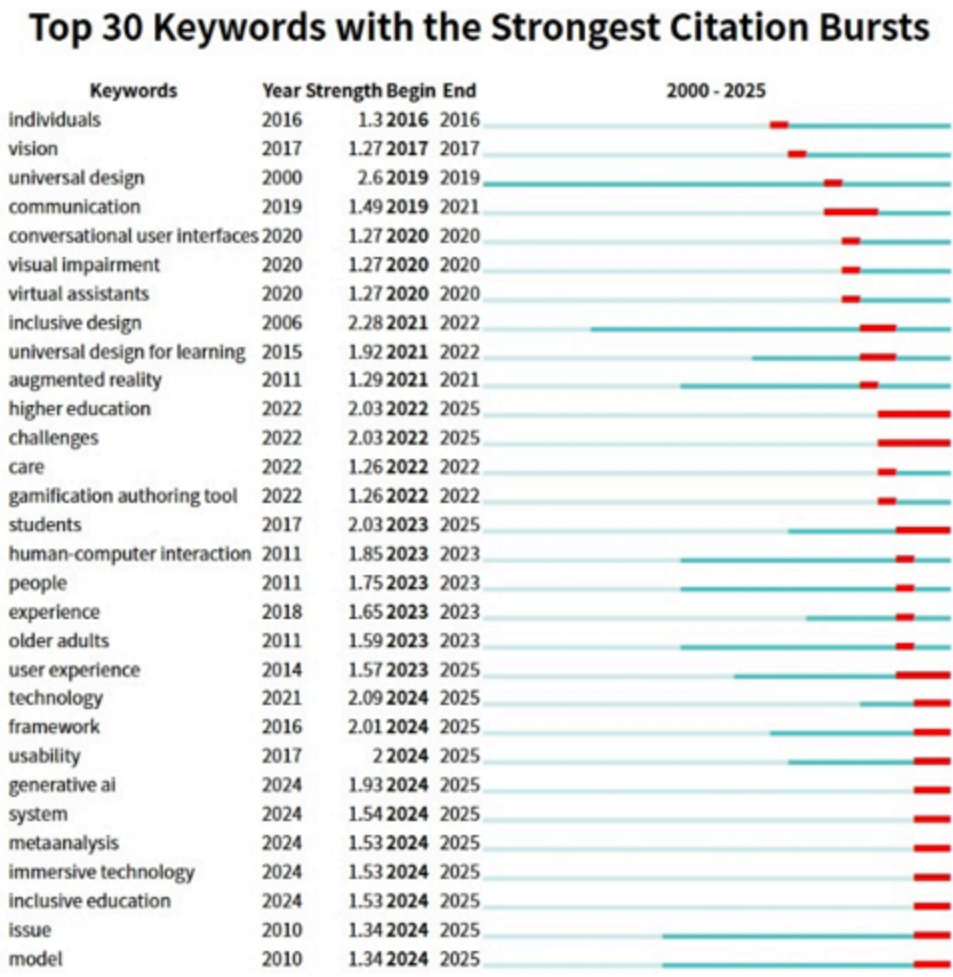


Figure 9

Top-30 keywords with the strongest citation bursts (2000–2025).

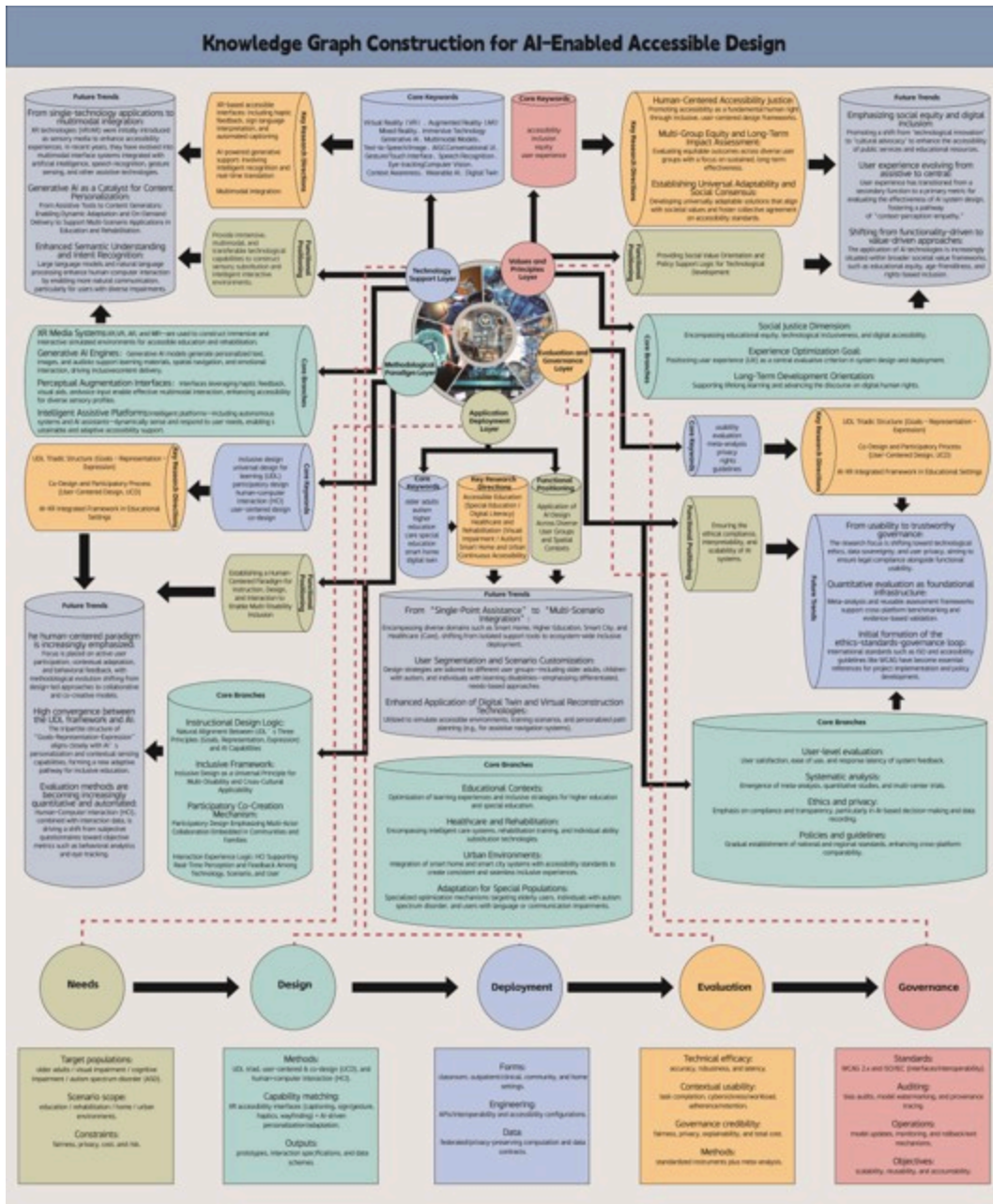


Figure 10

Knowledge Graph for AI-Enabled Accessibility Design.