

# Digital Education Fronts 2025

Project Team of Digital Education Fronts<sup>‡</sup>

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**Abstract** As the driving force of global educational transformation, digital education functions as a pragmatic vehicle for technology-driven innovation and a strategic path for advancing educational equity and fostering high-quality development. The Ministry of Education of the People's Republic of China (2024) issued the *Shanghai call for cooperation on digital education*, which underscored the imperative to ensure that digital education benefited everyone fairly and collaboratively advanced the United Nations' 2030 sustainable development goals. Reshaping the educational ecosystem through digital transformation, deepening the integration of teaching and AI technologies, and building an open, inclusive, and intelligent learning system have increasingly become a global consensus.

In response to this global imperative, *Frontiers of Digital Education* has consistently been tracking and reflecting international development in this field. Aiming to capture the forefront of international academic discourse and innovation, the journal launched a pioneering research project titled Digital Education Fronts 2025. This project aspires to provide intellectual leadership, contribute to the construction of a global digital education discourse, and promote practical innovation in this field.

The project was spearheaded by the journal's editorial office in collaboration with Clarivate and supported by a multidisciplinary research team. Utilizing a dataset of nearly 60,000 academic papers on digital education published worldwide from 2019 to 2024, the team conducted a comprehensive scientometric analysis using Clarivate's advanced analytical tools, combined with in-depth exploration by educational technology scholars. This process identified 66 significant thematic clusters, which were further refined through multiple rounds of expert review by a cross-disciplinary panel of scholars specializing in education, AI, and library and information science, ultimately resulting in the selection

of the top 10 critical fronts presented in this report.

This report consists of 3 main sections: Section 1 outlines the research framework, including the methodologies for data integration, the mechanisms of cross-institutional collaboration, and the procedures for topic selection; Section 2 provides a global research landscape in digital education; Section 3 focuses on the top 10 critical fronts and offers detailed insights supported by empirical cases and trend forecasting. These are interpreted through multiple perspectives, including technological iteration, policy coordination, and emergent ethical challenges. This report encapsulates a midterm analysis of global advancements in digital education and offers a forward-looking analysis of cutting-edge technologies, such as generative AI and immersive learning environments, as well as their applications in education. It serves as a strategic reference for educational digitalization over the next 5 to 10 years.

The identification, interpretation, and projection of research hotspots in digital education depend on coordinated innovation. Through this project, the editorial team has advanced the journal's mission to foster high-impact academic publishing, develop a specialized international academic platform, and refine its institutional infrastructure. It extends its heartfelt appreciation to all collaborating institutions and scholars, both domestic and foreign, for their invaluable contributions to this project.

## 1 Background and Methodological Framework

### 1.1 | Background

Amid the rapid advancement of information technology, digital education has emerged as a crucial direction for global educational reform. It is reshaping the traditional pedagogical models while creating new possibilities for resource sharing and educational equity. This research project employs a rigorous and

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multidimensional framework to identify and analyze the top 10 critical fronts in digital education, aiming to capture the latest developments and emerging trends. The goal is to provide valuable references for policy-makers, researchers, and practitioners in digital education.

The project is based on a collection of papers on digital education published globally over the past 6 years (2019–2024). First, the project leverages the platform of *Frontiers of Digital Education* and supports the strategic planning of digital education by continuously analyzing relevant literature to extract development directions, goals, and strategic priorities, offering evidence-based insights for policy and planning. Second, it strengthens the journal's academic leadership by focusing on cutting-edge topics, enhancing the novelty and foresight of its articles, and building an international academic exchange platform.

Four core objectives of the research project are as follows: first, to identify and interpret the critical fronts in digital education; second, to construct a framework for understanding critical fronts; third, to analyze their internal logic and developmental trajectories; fourth, to produce the top 10 critical fronts in digital education. This report includes a comprehensive overview, front explanations, trend forecasts, bibliometric analyses, and in-depth case studies, serving as an authoritative reference for both academia and industry.

## 1.2 | Methodological Framework

The report adopted mixed methods, combining quantitative analysis of bibliometrics with expert qualitative review, to offer a comprehensive and objective understanding of the field's key research directions. The research process followed 3 main stages: data mining, data analysis, and expert evaluation. **Data mining:** Library and information science specialists applied data mining techniques using search strategies based on expert-provided list of keyword, journal, and conference. This helped define the scope and ensured the systematic retrieval of relevant literature in digital education. **Data analysis:** Co-citation clustering was used to form thematic clusters, identify research issues, and analyze the core papers (see Appendix B) underpinning each theme. This step revealed development trends and geographic distributions across the field. **Expert evaluation:** Through rounds of thematic screening, naming revisions, and expert panel discussions, the most relevant topics were selected. To account for delays in publication data and ensure comprehensiveness, additional hotspot nominations and refinements were contributed by experts in relevant domains.

The primary data source was Clarivate's Web of

Science™ (WoS) Core Collection. An initial set of search queries was developed based on comprehensive literature reviews and expert consultations, focusing on the core concepts of digital education and covering the period from 2019 to 2024.

Drawing on a collection of nearly 60,000 global publications and their citation networks, the report identified critical frontiers. Highly cited papers were selected and matched with essential science indicators (ESI) research fronts derived from co-citation cluster analysis. This process yielded 45 critical fronts in digital education. These clusters were generated algorithmically based on citation patterns among papers, rather than through manual categorisation, thus reflecting organically emerging areas of scholarly focus. Building on this empirical foundation, expert evaluation was then used to identify the top 10 critical issues.

### 1.3 | Selection Process for the Top 10 Critical Fronts in Digital Education

The selection of the 10 global hot issues was based on a robust, iterative, and evidence-driven process comprising 3 principal stages: data acquisition and preprocessing; topic mining and cluster analysis; and expert evaluation and final selection.

#### 1.3.1 Literature Acquisition

Utilizing science citation index expanded (SCIE)- and social science citation index (SSCI)-indexed data from WoS, a comprehensive mapping of digital education-related technologies and their corresponding WoS subject categories was conducted. This enabled the construction of an inclusive list of relevant academic journals and conferences. After rounds of expert nomination, review, and revision, a final corpus of nearly 60,000 papers was identified, spanning 6,984 journals and 3,509 conferences. Following WoS guidelines for identifying highly cited papers, while adjusting for factors such as publication year (see Appendix B) and document type, 264 highly cited papers (top 1% by citation) published between 2019 and 2024 were selected.

#### 1.3.2 Topic Mining and Cluster Analysis

Based on the highly cited papers, a co-citation clustering method was applied to identify thematic fronts within digital education. Each cluster was composed of a set of core papers. Metrics such as the number of core papers, total citations, and mean publication year (see Appendix B) were used to characterise and rank the clusters. This process yielded 66 well-defined literature clusters representing critical fronts in global digital education research.

### 1.3.3 Expert Evaluation and Final Selection

The 66 clusters underwent critical scrutiny to eliminate redundant and tangential topics. Through surveys, workshops, and expert consultations, augmented by AI-assisted analysis, there are 45 clusters related to digital education remaining. After analysis and judgment by experts, the list was refined to 14 candidate hotspots. An expert panel conducted multiple rounds of validation, ultimately culminating in the determination of the top 10 critical fronts in digital education. This process ensures both empirical robustness and domain-specific relevance, reflecting the collective evaluation of interdisciplinary scholars and data-driven methodologies.

## 2 Global Research Landscape in Digital Education

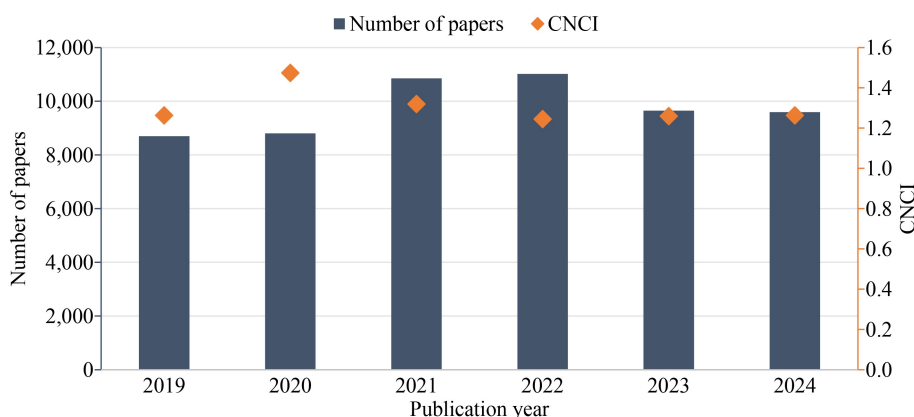
The digital transformation of education has emerged as a focus of educational reform and innovation worldwide. At its core, this transformation entails the deep integration of digital technologies into pedagogical practice, which is supported by the evolution of educational paradigms, the development of intelligent learning environments, the optimization of instructional methodologies, and the reform of assessment systems. The overarching objective is to construct a dynamic and sustainable ecosystem that interweaves digital pedagogy with data-driven educational governance. This section systematically reviews global research progress in digital education from 2019 to 2024. Through a multidimensional bibliometric analysis, it provides a panoramic view of development trends and research hotspots in this field, offering a comprehensive understanding of its global research landscape.

Overall, the annual number of papers in digital education remained relatively stable from 2019 to 2024, with over 8,000 papers published annually. A significant surge occurred in 2021 and 2022, with 10,853 and 11,021 publications, respectively. In terms of category normalized citation impact (CNCI, see Appendix B), a metric that reflects citation performance relative to global disciplinary norms, the field demonstrated consistently strong performance. The highest CNCI value was recorded in 2020 at 1.474, indicating a citation impact substantially above the cross-disciplinary average (see Figure 1).

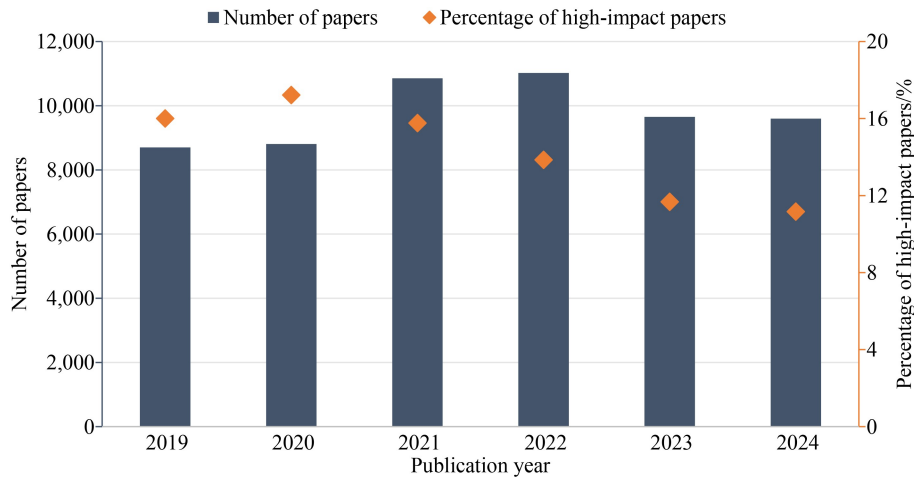
High-impact papers (see Appendix B), defined as those ranking in the top 10% of citations for a given discipline, publication year, and document type, exhibited a declining trend over the period from 2019 to 2024. After peaking at 17.22% in 2020, the percentage of high-impact papers fell to 11.17% by 2024. This significant decline suggests a potential stagnation in influential research output and underscores the need for further innovation and breakthroughs in the field (see Figure 2).

Papers produced through international collaboration serve as critical indicators of global academic engagement and are instrumental in enhancing the international visibility and influence of research. From 2019 to 2024, the percentage of internationally co-authored publications in digital education exhibited a steady upward trend, signaling growing transnational academic engagement. The interdisciplinary nature of digital education, especially its intersection with computer science and information technology, has facilitated its international collaborations, placing the field at a moderate level of collaborative intensity within the broader academic landscape (see Figure 3).

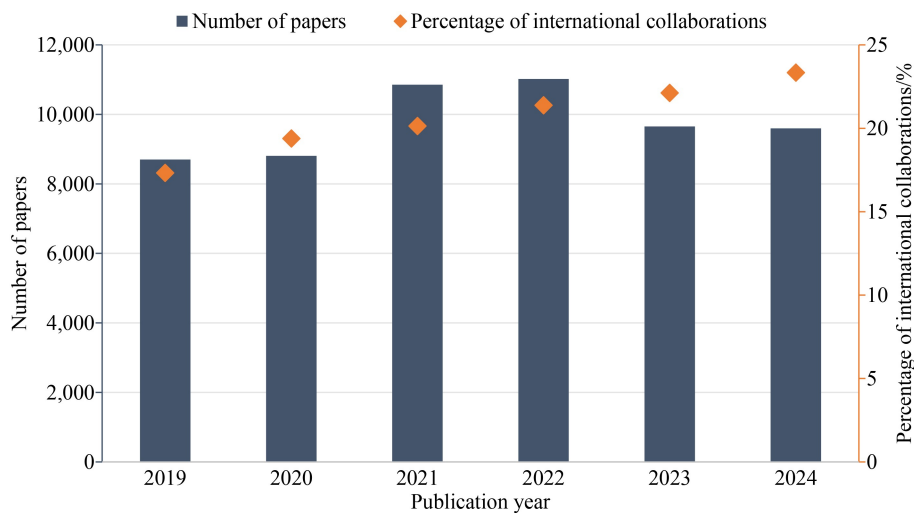
An analysis of national research output and citation performance from 2019 to 2024 reveals that, among the top 10 contributing countries, all except Brazil exceeded the global average in citation impact.



**Figure 1** Annual number of papers and CNCI index in the field of digital education (2019–2024). CNCI: category normalized citation impact.



**Figure 2** Annual number of papers and percentage of high-impact papers in digital education (2019–2024).



**Figure 3** Annual number of papers and percentage of international collaborations in digital education (2019–2024).

The USA and China emerged as the leading contributors in terms of number of papers, markedly outpacing countries such as Spain, the UK, and Australia. Chinese researchers demonstrated robust performance in both quantity and quality, ranking second globally in number of papers and third in citation impact. While the USA led in total output, it ranked sixth in impact. In contrast, Australia, despite ranking fifth in publication volume, achieved the highest citation impact, suggesting a research ecosystem characterized by lower but higher quality publications (see Figure 4).

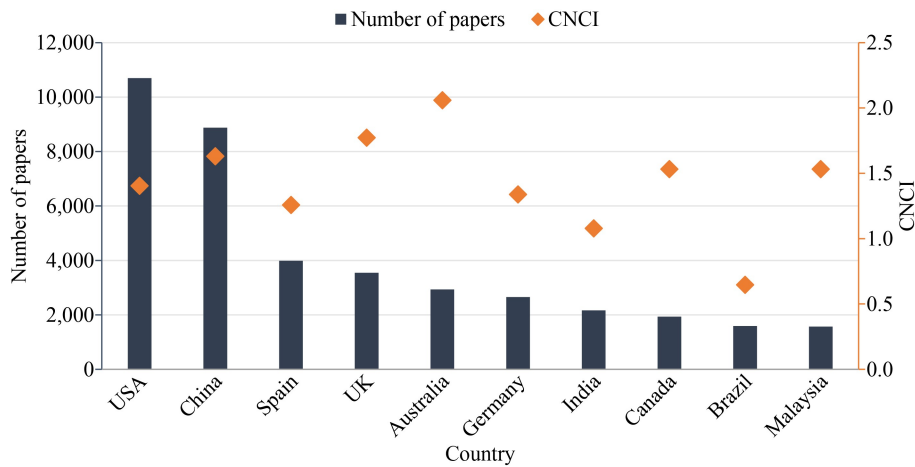
Australia led globally, with 22.60% of its digital education publications classified as high-impact, followed by the UK at 20.01%, and China at 18.40%. This percentage was higher than that of Canada (17.00%) and the USA (15.91%) (see Figure 5).

In terms of international research collaboration, the UK demonstrated exceptional performance,

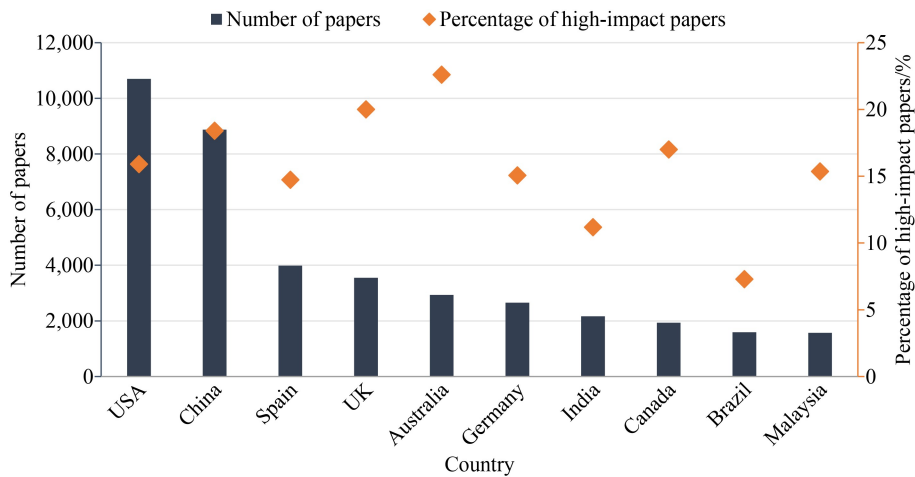
with more than 50% of its publications in digital education involving international co-authors. Malaysia, Australia, and Canada also exhibited strong collaborative engagement, with rates exceeding 45%. In contrast, despite their dominance in total publication output, both China and the USA had international co-authorship rates below 30%, indicating significant potential for growth in fostering international research partnerships (see Figure 6).

### 3 Top 10 Critical Fronts in Digital Education

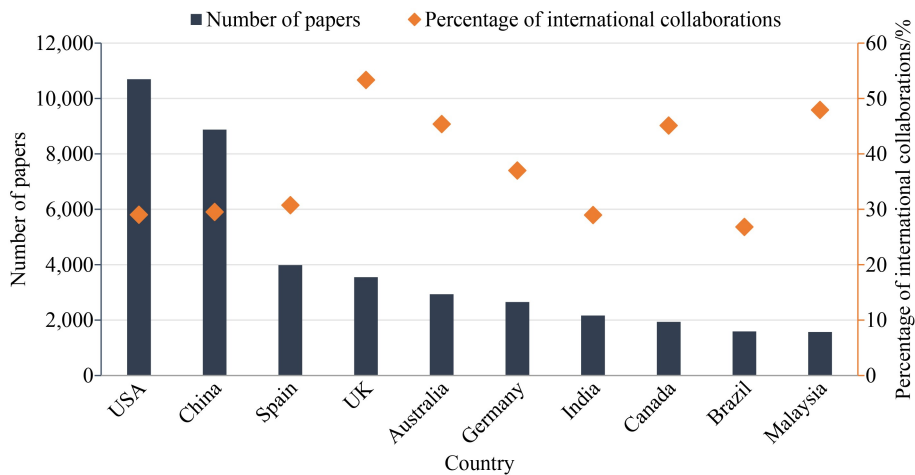
Core papers refer to highly cited papers positioned within the top 1% of citation frequency globally. From a quantitative analysis of core papers across nations, China led with 105 core papers between 2019 and 2024,



**Figure 4** Top 10 countries by number of papers in digital education and their CNCI indexes (2019–2024). CNCI: category normalized citation impact.



**Figure 5** Top 10 countries by number of papers in digital education and their percentages of high-impact papers (2019–2024).

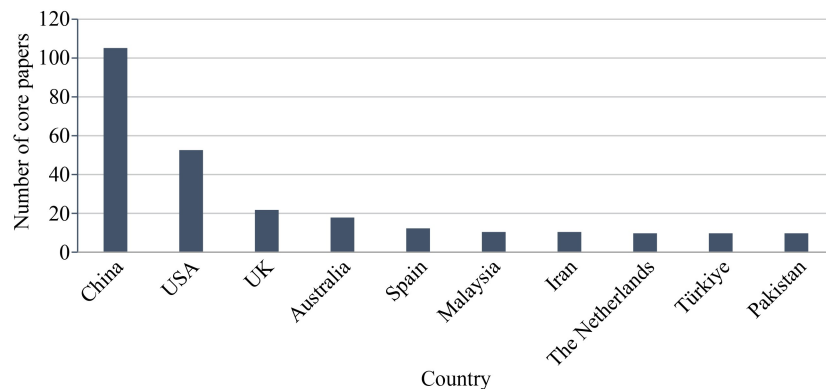


**Figure 6** Top 10 countries by number of papers in digital education and their percentages of international collaborations (2019–2024).

followed by the USA (53 core papers) and the UK (22 core papers). [Figure 7](#) presents the rankings of the top 10 countries in terms of core papers within the field of digital education during this period.

### 3.1 | Overview

The following top 10 critical fronts in digital education have emerged as the most prominent global research issues in the domain of digital education: generative AI accelerating interdisciplinary integration, metaverse technologies catalyzing smart learning paradigms, digital education transforming cognition of learning behaviors, AI empowering personalized learning: The future is now, digital literacy supporting teachers' professional development, human-AI collaboration reshaping digital education ecosystem, vocational education aligning with smart technology-driven innovation demands, global co-governance redefining ethical boundaries in digital education, digital education bridging regional gaps in the balanced development, and data driving intelligent decision-making across the entire teaching process (refer to [Table 1](#) for the complete list and [Table 2](#) for core papers from 2019 to 2024 associated with each topic).



**Figure 7** Top 10 countries by number of core papers in digital education (2019–2024).

**Table 1** Top 10 critical fronts in digital education

No.	Top 10 critical fronts in digital education	Number of core papers	Total citations	Average citations per paper	Mean publication year
1	Generative AI accelerating interdisciplinary integration	75	2,285	30.47	2023.3
2	Metaverse technologies catalyzing smart learning paradigms	73	7,052	96.60	2022.2
3	Digital education transforming cognition of learning behaviors	46	4,765	103.59	2022.0
4	AI empowering personalized learning: The future is now	42	2,550	60.71	2022.9
5	Digital literacy supporting teachers' professional development	37	5,061	136.78	2021.0
6	Human-AI collaboration reshaping digital education ecosystem	37	2,892	78.16	2022.6
7	Vocational education aligning with smart technology-driven innovation demands	32	5,106	159.60	2022.2
8	Global co-governance redefining ethical boundaries in digital education	17	1,717	101.00	2023.0
9	Digital education bridging regional gaps in the balanced development	9	1,398	155.33	2021.6
10	Data driving intelligent decision-making across the entire teaching process	4	1,823	455.75	2019.3

#### 3.1.1 Generative AI Accelerating Interdisciplinary Integration

Generative AI (GenAI) refers to a type of AI technology capable of generating original content across various formats, such as text, audio, imagery, and video, through supervised or unsupervised training. Unlike artificial general intelligence, which aims to replicate human-level reasoning across a broad range of tasks, GenAI is specifically focused on content creation. The integration of GenAI across disciplines has become a prominent research focus, with studies emphasizing GenAI as a tool embedded within traditional academic fields. This has sparked widespread academic interest in how GenAI drives interdisciplinary integration. Current research on this integration focuses on 6 primary areas:

(1) Personalized intelligent curriculum development, using GenAI to generate interdisciplinary learning materials tailored to students' academic backgrounds;

(2) Cross-linguistic knowledge exchange, leveraging AI tools to overcome language barriers and facilitate multilingual and cross-cultural communication;

**Table 2** Number of core papers published annually on the top 10 critical fronts in digital education

No.	Top 10 critical fronts in digital education	2019	2020	2021	2022	2023	2024
1	Generative AI accelerating interdisciplinary integration	0	1	2	4	32	36
2	Metaverse technologies catalyzing smart learning paradigms	8	7	7	12	20	19
3	Digital education transforming cognition of learning behaviors	7	5	6	4	12	12
4	AI empowering personalized learning: The future is now	2	1	2	4	17	16
5	Digital literacy supporting teachers' professional development	5	9	10	9	1	3
6	Human-AI collaboration reshaping digital education ecosystem	2	5	1	4	9	16
7	Vocational education aligning with smart technology-driven innovation demands	9	8	7	4	2	2
8	Global co-governance redefining ethical boundaries in digital education	0	1	1	1	8	6
9	Digital education bridging regional gaps in the balanced development	1	3	0	2	1	2
10	Data driving intelligent decision-making across the entire teaching process	3	1	0	0	0	0

(3) AI-enhanced scientific research, utilizing GenAI in experimental design and data analysis;

(4) Reconstructing ethical education frameworks, designing interdisciplinary ethics curricula;

(5) Innovation in intelligent assessment systems;

(6) Human-machine collaborative ecosystems.

Future research will focus on the deep integration of GenAI in interdisciplinary education, the co-development of science, technology, engineering, and mathematics (STEM) and humanities fields, and the exploration of human-AI collaboration to enhance cognitive abilities and team efficacy.

### 3.1.2 Metaverse Technologies Catalyzing Smart Learning Paradigms

The construction of smart learning environments refers to the creation of immersive, interactive, and personalized educational spaces using digital technologies such as the metaverse, virtual reality (VR), and AI. These environments seek to seamlessly integrate technologies with pedagogical objectives, thereby fostering more effective and engaging educational experiences. Research in this field typically explores 3 key areas:

(1) Technologically enriched learning environments, which investigate how emerging technologies, such as the metaverse, VR, and GenAI, can be integrated into educational contexts to create highly interactive and immersive learning experiences;

(2) Diversification of learning pathways on digital platforms, which examines how digital environments shape learner motivation, cognitive load, and academic performance through personalized and self-regulated learning trajectories;

(3) Breakthroughs in smart learning space construction and the integration of information technology with educational ecosystems.

Empirical findings suggest that well-designed immersive environments significantly enhance learner

engagement and knowledge retention. However, the introduction of excessively complex interfaces may elevate cognitive load, thereby diminishing educational efficacy. Gamification strategies have been shown to amplify intrinsic motivation and encourage active learning participation. GenAI further augments these environments by enabling adaptive instruction and highly personalized feedback. Anticipated future developments in smart learning spaces will likely emphasize multimodal interactivity, adaptive pedagogical pathways, learning analytics, and integrated assessment systems. The ultimate vision is the creation of intelligent, personalized, and seamlessly orchestrated learning experiences tailored to individual learner needs.

### 3.1.3 Digital Education Transforming Cognition of Learning Behaviors

The cognition of learning behavior in digital education encompasses the application of advanced technologies, such as educational data mining and multimodal learning analytics, to capture, analyze, and model learners' behavioral trajectories, cognitive load, and affective states in real time. These efforts aim to elucidate underlying cognitive mechanisms, identify learning patterns, and discern individualized learner profiles within technology-enhanced learning environments. Research is generally divided into 3 main areas:

(1) Multimodal data fusion for behavioral tracking, leveraging diverse data streams, such as facial expressions, keystroke dynamics, speech, and gesture recognition, to construct comprehensive behavioral representations and quantitative models of learning behaviors;

(2) Learning behavior modeling, where logs, eye-tracking, and electroencephalogram signals are used to create mappings between learners' behaviors and cognitive states, for example, using machine learning algorithms to identify cognitive styles or levels

of engagement;

(3) Affective computing for personalized learning, using behavior data to dynamically recommend learning paths, resources, or intervention strategies, such as the development of adaptive learning systems.

Looking ahead, research is expected to advance in the following 4 directions: enhanced real-time cognitive state monitoring; multimodal learning analytics platforms; intelligent tutoring systems with implementation of AI-enabled instructional agents capable of delivering personalized pedagogical guidance, emotional scaffolding, and self-regulation support; expansion of research into hybrid, blended, and metaverse-based learning environments, thereby facilitating more comprehensive and ecologically valid analysis of multimodal behavior across varied educational settings.

### *3.1.4 AI Empowering Personalized Learning: The Future Is Now*

AI empowering personalized learning refers to the deployment of AI technologies to address learner heterogeneity through the integration of insights from cognitive science, educational psychology, and related disciplines. The objective is to construct detailed learner profiles, algorithmically align educational content with learner needs, implement adaptive instructional strategies, and deliver dynamic, feedback-driven learning experiences. Research in AI empowering personalized learning is focused on 4 key areas: precision learner profiling, intelligent content recommendation, AI-augmented pedagogical strategies, and dynamic and formative assessment mechanisms. Research indicates that the evolution of AI empowering personalized learning has undergone a significant transformation from conventional classroom-based and instructor-led tutoring models, to AI-assisted exploratory learning, followed by the adoption of online education platforms and self-adaptive algorithms. This progression has culminated in the current phase of deep integration, wherein GenAI technologies and Big Data underpin comprehensive, full-cycle intelligent decision-making and feedback mechanisms. Key research achievements in this regard include:

(1) The deployment and refinement of technological applications within online education platforms, with particular emphasis on speech recognition, conversational agents, user behavior analysis, and affective computing in language acquisition contexts;

(2) The systematic management and evaluative frameworks for GenAI, focusing on its utility in knowledge tracing, personalized learning trajectory design, collaborative regulation strategies, and instructional architecture.

In general, research is centered on multi-source

data integration, full-dimensional intelligent feedback, and adaptive, dynamically responsive regulation. The overarching objective is to construct a forward-looking educational ecosystem that not only accommodates diverse individualized learning pathways but also exhibits high levels of intelligence, systemic coherence, and capacity for continuous enhancement.

### *3.1.5 Digital Literacy Supporting Teachers' Professional Development*

Teachers' digital literacies encompass the awareness, competencies, and ethical responsibilities required to proficiently leverage digital technologies for accessing, processing, managing, and evaluating digital content and resources. It also involves the ability to diagnose, analyze, and resolve pedagogical challenges while enhancing, innovating, and transforming educational practices. The foundational framework of digital literacy includes digital awareness, digital technology knowledge and skill, application capability, digital social responsibility, and sustained professional development. Key research areas in this domain primarily fall into 3 categories:

(1) Analyses of teachers' adoption of digital technologies and the factors influencing this adoption, with a particular focus on how personal attributes and perceived technological affordances affect the integration of AI and related tools into instructional settings;

(2) Studies on the development of digital competencies among educators, emphasizing the formulation of literacy frameworks tailored to digital media environments and contemporary pedagogical paradigms;

(3) Research on teachers' psychological adaptation to digitally mediated teaching, examining aspects such as mental health, well-being, occupational stress, and burnout, particularly under crisis conditions, alongside coping strategies.

Future trends will focus on differential impacts of various digital tools on instructional efficacy, teacher well-being, and professional development. They also emphasize the construction of multidimensional pathways for cultivating digital literacies, the establishment of robust and comprehensive assessment models, and the refinement of personalized, practice-oriented, and digitally integrated professional development frameworks supported by long-term institutional mechanisms.

### *3.1.6 Human-AI Collaboration Reshaping Digital Education Ecosystem*

Human-AI collaboration reshaping digital education ecosystem represents a prominent and rapidly evolving

research front that combines technological capabilities with humanistic values to propel educational innovation. This paradigm is underpinned by interdisciplinary insights from cognitive science and AI, facilitating a cooperative dynamic wherein AI systems augment human educators across critical pedagogical domains, such as knowledge dissemination, skills cultivation, and value formation. It aims to build an adaptive, interactive, and feedback-driven educational ecosystem. Current research efforts center around 4 principal directions:

- (1) The development of intelligent instructional tools designed to enhance learning efficacy through real-time, interactive engagement;
- (2) The creation of hybridized physical–virtual learning environments, fostering immersive and context-rich virtual classrooms;
- (3) The integration of emotionally intelligent learning support systems through the construction of dual-track cognitive–emotional frameworks;
- (4) The reconfiguration of collaborative learning models to better align with AI-mediated instructional dynamics.

### *3.1.7 Vocational Education Aligning with Smart Technology-Driven Innovation Demands*

Research on vocational education aligning with smart technology-driven innovation demands seeks to construct a digitally enabled educational ecosystem that seamlessly integrates industrial needs with educational provision, thereby achieving dynamic alignment between educational supply and labor market needs. This domain exemplifies an interdisciplinary fusion of educational theory, computer science, and engineering, operationalized through system-level interventions encompassing school–enterprise partnerships, curricular redesign, and talent pipeline optimization. In addressing the multifaceted challenges associated with the intelligent transformation of vocational education—such as evolving industrial requirements in terms of scale, structure, and skills; deficits in instructors' digital competencies; cognitive and cultural resistance to digitalization; outdated curriculum resources; and the absence of integrated virtual-physical training infrastructure—research focuses on 3 key dimensions:

- (1) The development of systematic frameworks to support high-quality vocational education, including the dual-integration of instructional content and occupational knowledge and the structural deepening of vocational knowledge networks;
- (2) The exploration of transformative pedagogical pathways employing virtual simulations and intelligent guidance systems to facilitate a shift from standardized instructional delivery to personalized, learner-centered models;

- (3) The utilization of digital platforms to integrate diverse educational resources, enabling the construction of an interactive cloud-based smart learning environment and promoting the intelligent advancement of faculty development initiatives.

### *3.1.8 Global Co-Governance Redefining Ethical Boundaries in Digital Education*

Although a universally accepted definition of ethical principles in digital education has yet to be established, existing research generally focuses on how to balance the instrumental value of digital technologies with their ethical implications within educational contexts. Central to this discourse are core principles such as educational equity, privacy protection, and information security. Current research on ethical framework in digital education primarily encompasses 4 dimensions:

- (1) Equitable access to digital educational resources, examining strategies to ensure inclusive participation by all learners, particularly marginalized populations, while preventing the exacerbation of educational inequality caused by the digital divide;
- (2) Ethical regulatory frameworks for digital technologies, investigating mechanisms for the identification, assessment, and mitigation of ethical risks, including cognitive biases and algorithmic discrimination, thereby safeguarding fairness and integrity in algorithmically mediated educational processes;
- (3) Delineation of rights and responsibilities among educational stakeholders, articulating the ethical obligations and entitlements of educators, learners, platform providers, and guardians within a complex digital education ecosystem, and advancing governance models grounded in the equitable distribution of accountability;
- (4) Pathways for global collaborative governance, exploring the harmonization of ethical principles amid divergent legal, cultural, and policy frameworks in the transnational expansion of digital education.

In summary, the future development of ethical principles in digital education will continue to seek a balance between technological innovation and moral responsibility. The overarching goals will be to enhance educational equity, strengthen privacy protection, and optimize the use of technology, while fostering the harmonious coexistence of education and technology.

### *3.1.9 Digital Education Bridging Regional Gaps in the Balanced Development*

Research on the digital education is bridging regional gaps in the balanced development driven by the need to address spatial disparities in the allocation of educational resources. Drawing on the theories of

educational equity and technology diffusion, the research spans 5 key areas:

(1) Equalization of digital infrastructure, analyzing the underlying mechanisms and pathways for ensuring equitable access to basic digital infrastructure across regions;

(2) Resource-sharing frameworks, facilitating cross-regional circulation and co-utilization of educational content and platforms to enable the strategic redistribution of high-quality educational resources from more developed regions to less developed ones;

(3) Teachers' mutual support and capacity building, designing systemic models for inter-regional collaboration in teachers' professional development;

(4) Cross-regional collaborative innovation, leveraging digital connectivity to establish interlinked educational communities;

(5) Strategies for sustainable and balanced regional development, constructing long-term frameworks for the equitable expansion of digital educational ecosystems.

### *3.1.10 Data Driving Intelligent Decision-Making Across the Entire Teaching Process*

Data driving intelligent decision-making across the entire teaching process represents a paradigmatic shift in digital education, wherein empirical evidence replaces intuition as the basis for pedagogical decisions. This model hinges on the comprehensive collection, integration, and analysis of heterogeneous educational data to optimize the design, implementation, evaluation, and continuous improvement of instructional practices. Anchored in the “data–information–knowledge–wisdom” hierarchy, it advocates a closed-loop feedback system encompassing lesson planning, classroom interaction, formative assessment, and outcome evaluation. The value of this paradigm lies in two key areas: enhancing the scientific rigor of educational decisions through continuous data feedback and enabling personalized, differentiated instruction. Current research focuses on 4 critical areas:

(1) Decision-making architectures based on multimodal data integration and intelligent analytics, overcoming the limitations of traditional unimodal approaches by establishing collaborative frameworks for cross-modal data synthesis;

(2) Theoretical–technical convergence, translating classical educational theories into computational cognitive development models that inform decision logic;

(3) Development of teachers' data literacy, establishing comprehensive training ecosystems that support data competencies across all stages of educators' professional lifecycles;

(4) Construction of data ethics and governance

systems, ensuring that data usage aligns with ethical standards, privacy protections, and institutional accountability.

Emerging trends emphasize enhanced intelligence and system-wide integration, focusing on real-time decision-making empowered by GenAI, the fusion of multimodal learning analytics, the strategic cultivation of educators' data literacy, and the collaborative development of ethical frameworks and evidence-based evaluation systems to guide educational practice in the digital era.

## **3.2 | Top 10 Critical Fronts in Digital Education: Interpretation and Analysis**

### *3.2.1 Generative AI Accelerating Interdisciplinary Integration*

GenAI, a cutting-edge field within contemporary AI research, is fundamentally driven by advancements in natural language processing (NLP). This technology empowers sophisticated human–machine interactions and the generation of high-quality text with semantic coherence and logical structure. By harnessing large-scale pre-trained language models and deep neural networks, GenAI demonstrates advanced capabilities in contextual comprehension and content creation. GenAI accelerating interdisciplinary integration research is of critical strategic importance. First, this approach contributes to promoting the integration and reconfiguration of educational resources, breaking down traditional disciplinary boundaries, and advancing the transformation of education models towards intelligence and modernization. Second, it cultivates high-caliber talents endowed with an interdisciplinary mindset and innovative competencies. Third, by implementing GenAI in multilingual and multicultural education, it bridges linguistic divides, provides a global communication platform, promotes the internationalization of educational resources, and enhances the efficiency of global educational collaboration and exchange.

Prior to 2021, AI-related research primarily centered on conventional topics, such as underlying technologies for service-oriented applications, algorithmic ethics, and fundamental theories. The release of ChatGPT in November 2022 precipitated the emergence of GenAI as both an independent research fronts and a catalyst for interdisciplinary integration and innovation. From 2023 to the present, related research outputs have demonstrated an exponential growth trajectory.

The current GenAI-facilitated interdisciplinary integration is characterized by 6 principal research hotspots:

(1) Personalized intelligent curriculum development. Through NLP technologies, this research

direction focuses on auto-generating interdisciplinary curriculum systems tailored to students' cognitive levels (e.g., constructing intelligent tutoring systems based upon knowledge graphs). The system dynamically adjusts content difficulty according to the needs of learners with diverse academic backgrounds.

(2) Cross-linguistic knowledge integration mechanisms. Research in this direction concentrates on developing intelligent translation engines powered by multimodal large language models to achieve semantic-level cross-lingual conversion of educational resources, while simultaneously constructing universal knowledge frameworks for learners across cultural contexts.

(3) AI-augmented scientific research experiments. With the assistance of GenAI, feasible experimental protocols can be generated (e.g., automatically designing molecular synthesis pathways or optimizing parameters of medical image analysis models through genetic algorithms).

(4) Reconstruction of technology ethics education. The studies of this direction develop GenAI-based academic integrity monitoring systems that utilize adversarial scenario generation techniques to simulate ethical dilemmas (e.g., data privacy issues and intellectual property), thereby enhancing ethical reasoning and decision-making capacities.

(5) Innovation in intelligent assessment systems. Scholarly efforts are invested to construct multidimensional evaluation frameworks that employ reinforcement learning algorithms to dynamically calibrate the interdisciplinary depth of assessment items, and quantify learners' cross-disciplinary thinking capacity through concept network analysis.

(6) Development of human-AI collaborative ecosystems. Extending the traditional technology acceptance model, the studies of this direction incorporate perceived value metrics for interdisciplinary collaboration, establishing AI education application evaluation frameworks that encompass knowledge-sharing mechanisms and trust-building strategies.

In this research hotspot, the top 3 countries by core paper output are China, the USA, and Iran; the same 3 countries also take the lead in total citation counts; the highest average citations per paper are observed in Bulgaria, India, and the UK (see Table 3). Meanwhile, the USA, China, Türkiye and the UK demonstrate the highest degrees of international collaboration among high-output countries (see Figure 8). The top 3 institutions by core paper output are Nanjing Normal University, North China University of Water Resources and Electric Power, and Henan University; institutions with the highest average citation per paper include University of Chinese Academy of Sciences, University of Science and Technology Beijing, and Beijing University of Technology (see Table 4). Notably, Nanjing Normal University and North China University of Water Resources and Electric Power exhibit the highest degree of collaboration among the major institutions producing core papers (see Figure 9). The top 3 countries by the number of citing core papers are China, the USA, and India (see Table 5). The top 3 institutions by the number of citing core papers are Beijing University of Technology, Northeastern University (China), and Guangdong University of Technology (see Table 6). Figure 10 presents the developmental roadmap for generative AI accelerating interdisciplinary integration.

### 3.2.2 Metaverse Technologies Catalyzing Smart Learning Paradigms

As a pivotal conduit for the digital transformation of education, smart learning environments are undergoing a profound transformation from single-technology applications to multi-technology integration, which drives the continuous iteration of smart learning paradigms. In recent years, metaverse-enabled learning environments, characterized by their high immersiveness, real-time interactivity, and extended reality technologies, can create instructional scenarios that are difficult to achieve in real-world contexts. They provide

**Table 3** Major countries producing core papers on generative AI accelerating interdisciplinary integration

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	52	69.33	3,168	60.92	2023.3
2	USA	13	17.33	855	65.77	2023.2
3	Iran	9	12.00	465	51.67	2023.6
4	UK	5	6.67	416	83.20	2023.2
5	Türkiye	5	6.67	168	33.60	2023.2
6	Pakistan	4	5.33	132	33.00	2023.8
7	Republic of Korea	3	4.00	234	78.00	2023.3
8	Saudi Arabia	3	4.00	100	33.33	2024.0
9	Bulgaria	2	2.67	235	117.50	2023.0
10	India	2	2.67	228	114.00	2023.0

multimodal sensory experiences, enabling learners to transform from passive recipients to active explorers and knowledge constructors. Research indicates that immersive VR exerts significantly positive effects on learners' science education and specific competency development, showing advantages over traditional lecturing or hands-on learning. Nonetheless, this technology poses a risk of excessive cognitive overload, necessitating in-depth systematic assessment and strategic research.

Current research primarily coalesces around the following 3 aspects:

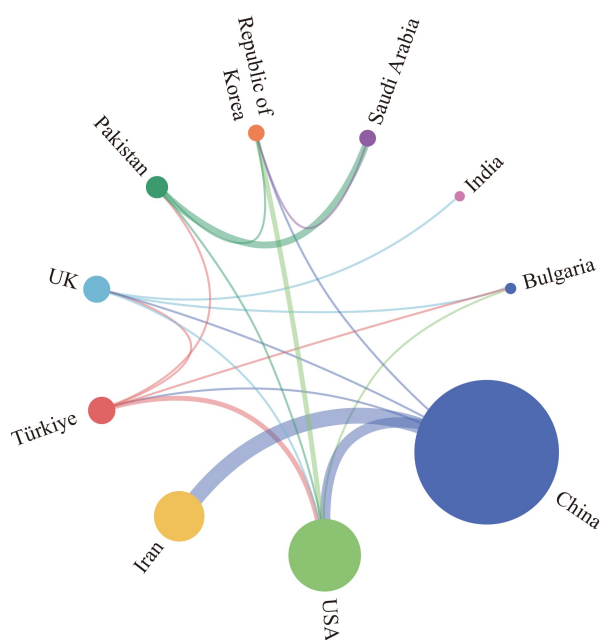
(1) The GenAI-enabled transformation of interaction and content generation in smart learning

environments. This area includes issues of the relationship between the acceptance of GenAI and users' cognitive understanding of the technology, learners' intrinsic psychological needs and emergent cognitive models, as well as effective mechanisms to enhance sustained engagement with digital learning environments.

(2) The integration of diversified pedagogical methods in smart learning environments. Research in this direction explores ways to optimize learners' engagement and learning outcomes, to design personalized, experience-driven learning pathways, and, in particular, to investigate the role of computer-based cognitive tools in cultivating higher-order thinking skills and promoting reflective learning.

(3) The transformation of pedagogical models, evaluation methods, and learning theories brought about by the construction of smart learning environments. This direction concerns the effectiveness of smart learning environments, the synergistic effects of multiple factors, etc., with a particular focus on the integration of technology into the educational ecosystem.

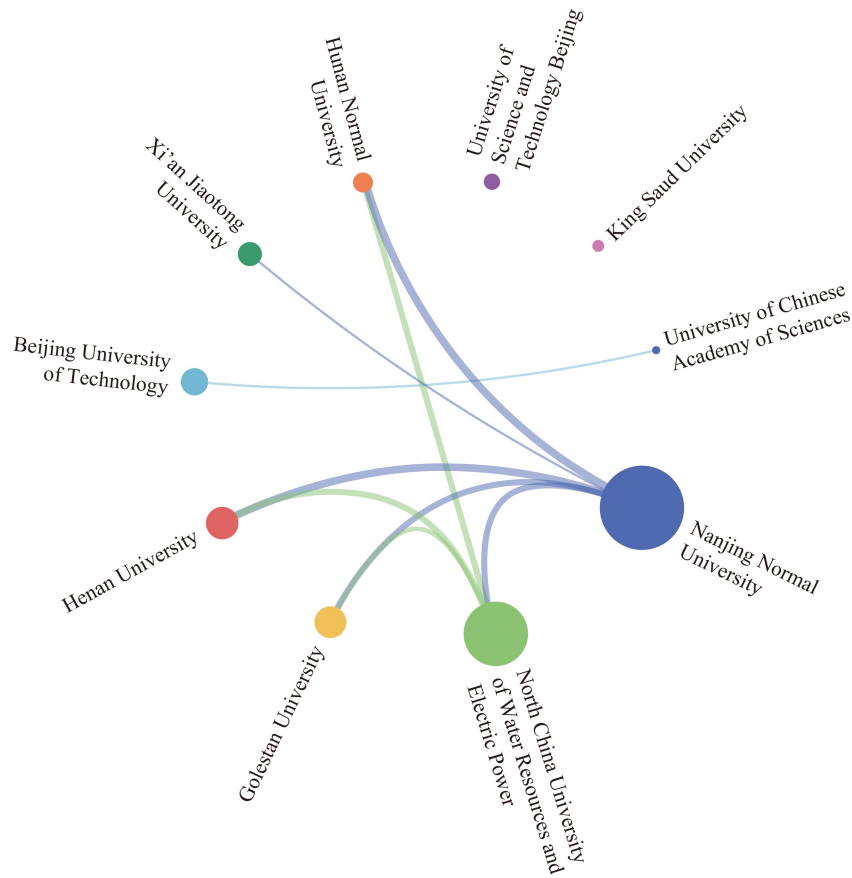
In this research hotspot, the top 3 countries by core paper output are China, the USA, and Pakistan; the top 3 countries by total citations are China, the USA, and Denmark; the highest average citations per paper are recorded in Denmark, the USA, and the UK (see Table 7). Countries with the most extensive international collaborations include China, the USA, Türkiye, and Pakistan (see Figure 11). The top 3 institutions by core paper output are University of Copenhagen, Beijing University of Technology, and University of California, Santa Barbara; institutions with the highest average citations per paper include University of Turku, Tampere University, and University of California, Santa Barbara (see Table 8). Institutions that demonstrate the highest degree of international co-authorship include Beijing University of Technology, University of Engineering and Technology Lahore, University of



**Figure 8** Collaboration network among major countries producing core papers on generative AI accelerating interdisciplinary integration.

**Table 4** Major institutions producing core papers on generative AI accelerating interdisciplinary integration

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Nanjing Normal University	19	25.33	1,002	52.74	2023.5
2	North China University of Water Resources and Electric Power	16	21.33	457	28.56	2023.9
3	Henan University	8	10.67	547	68.38	2023.3
4	Golestan University	8	10.67	456	57.00	2023.5
5	Beijing University of Technology	7	9.33	786	112.29	2022.0
6	Xi'an Jiaotong University	6	8.00	312	52.00	2023.5
7	Hunan Normal University	5	6.67	149	29.80	2024.0
8	University of Science and Technology Beijing	4	5.33	524	131.00	2021.3
9	King Saud University	3	4.00	100	33.33	2024.0
10	University of Chinese Academy of Sciences	2	2.67	498	249.00	2021.5



**Figure 9** Collaboration network among major institutions producing core papers on generative AI accelerating interdisciplinary integration.

**Table 5** Major countries citing core papers on generative AI accelerating interdisciplinary integration

No.	Country	Number of citing papers/%	Percentage of citing papers/%	Mean citing year
1	China	1,342	58.73	2023.4
2	USA	309	13.52	2023.6
3	India	119	5.21	2023.9
4	UK	108	4.73	2023.9
5	Republic of Korea	91	3.98	2023.8
6	Malaysia	76	3.33	2024.0
7	Iran	75	3.28	2023.8
8	Saudi Arabia	75	3.28	2024.0
9	Türkiye	67	2.93	2024.0
10	Australia	66	2.89	2023.8

Copenhagen, etc. (see Figure 12). With regard to citation impact, the top 3 citing countries are China, the USA, and Spain (see Table 9). The most active institutions citing core papers include Tampere University, The University of Hong Kong, and The Hong Kong Polytechnic University (see Table 10). Figure 13 presents the developmental roadmap for

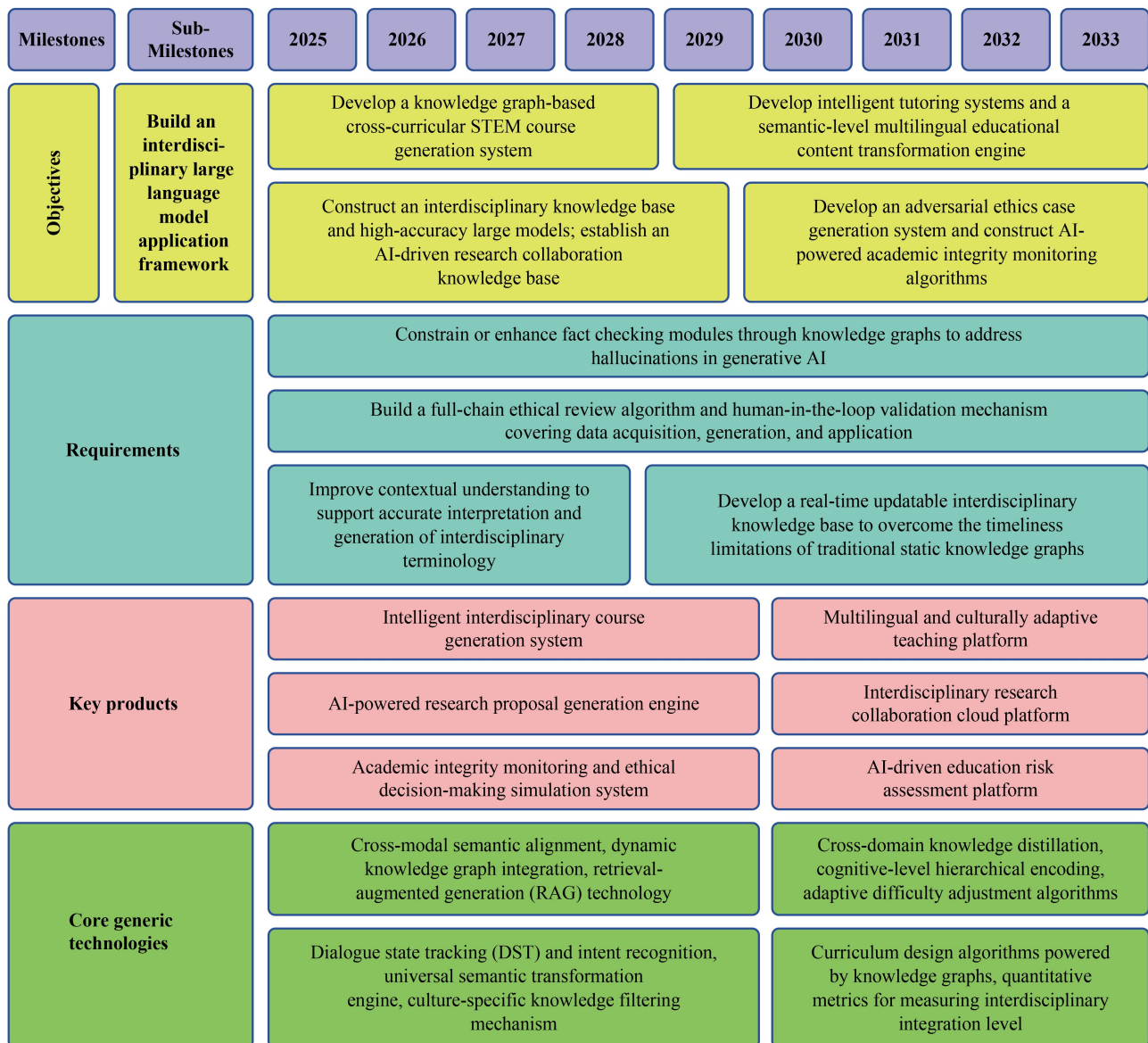
metaverse technologies catalyzing smart learning paradigms.

### 3.2.3 Digital Education Transforming Cognition of Learning Behaviors

Digital education transforming cognition of learning

**Table 6** Major institutions citing core papers on generative AI accelerating interdisciplinary integration

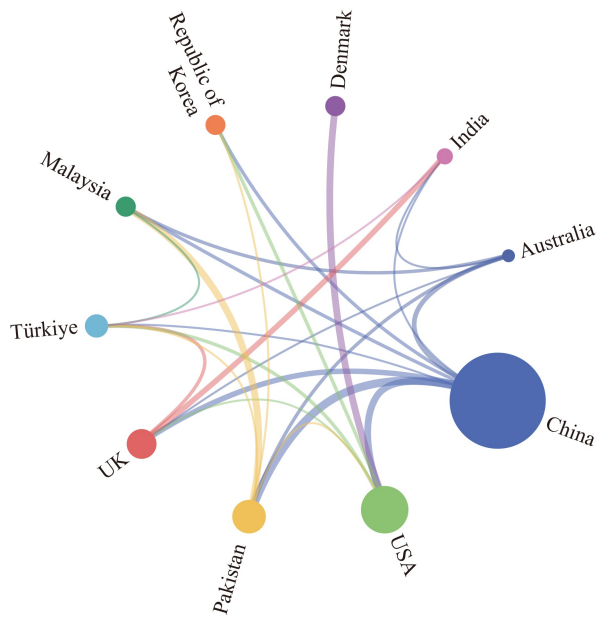
No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	Beijing University of Technology	134	6.04	2022.9
2	Northeastern University (China)	69	3.11	2022.8
3	Guangdong University of Technology	59	2.66	2022.4
4	Nanjing Normal University	47	2.12	2023.8
5	Beijing Normal University	46	2.07	2023.1
6	University of Science and Technology Beijing	45	2.03	2022.2
7	Chinese Academy of Sciences	41	1.85	2022.4
8	University of Illinois Chicago	41	1.85	2022.7
9	Henan University	37	1.67	2023.5
10	South China University of Technology	37	1.67	2022.5



**Figure 10** Developmental roadmap for generative AI accelerating interdisciplinary integration. STEM: science, technology, engineering, and mathematics.

**Table 7** Major countries producing core papers on metaverse technologies catalyzing smart learning paradigms

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	28	38.36	2,244	80.14	2022.6
2	USA	14	19.18	1,644	117.43	2022.4
3	Pakistan	10	13.70	362	36.20	2023.6
4	UK	9	12.33	850	94.44	2022.3
5	Türkiye	8	10.96	319	39.88	2023.0
6	Denmark	6	8.22	1,556	259.33	2020.7
7	Republic of Korea	6	8.22	474	79.00	2023.0
8	Malaysia	6	8.22	166	27.67	2023.7
9	India	5	6.85	368	73.60	2023.2
10	Australia	4	5.48	165	41.25	2023.5



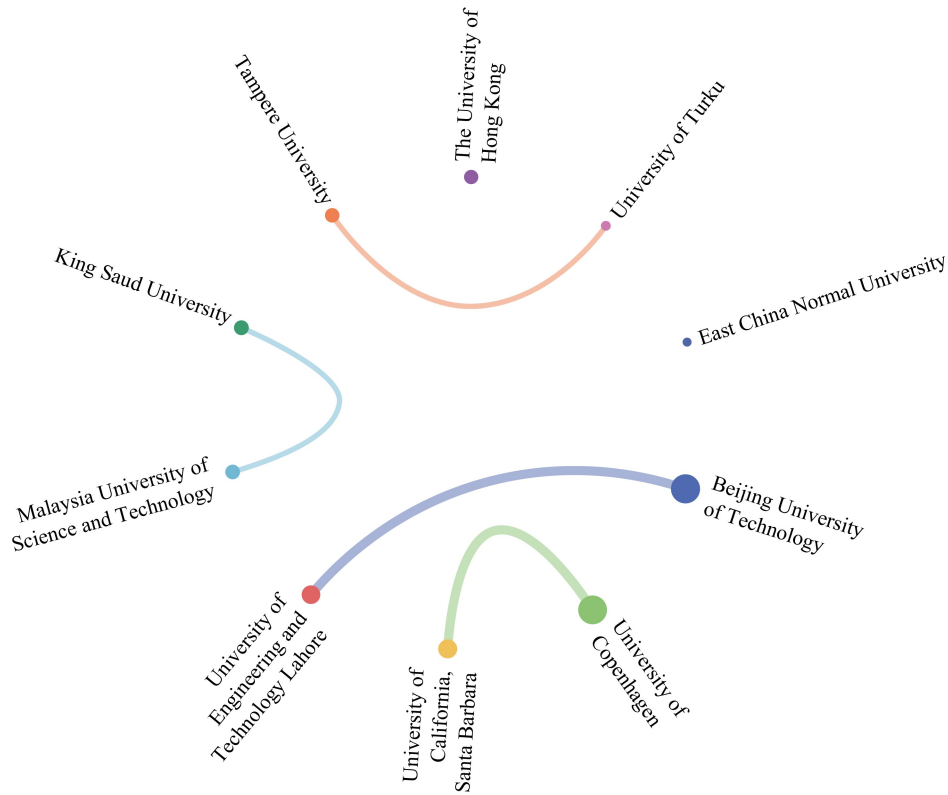
**Figure 11** Collaboration network among major countries producing core papers on metaverse technologies catalyzing smart learning paradigms.

behaviors represents a critical front in the ongoing progression of educational informatization and intelligentization. At its foundation, this field harnesses advanced information technologies to quantitatively analyze and model learners’ cognitive processes. Through multidimensional and multimodal data collection and analysis, this line of inquiry provides robust empirical evidence and technological underpinnings for elucidating learning patterns, optimizing pedagogical strategies, and advancing the implementation of personalized education. This research area holds particular significance in 4 respects: It employs multimodal data fusion techniques to decode the “cognitive black box” problem, enabling visualization and quantification of cognitive mechanisms; it fosters a paradigmatic shift in educational assessment from outcome-based metrics to process-oriented evaluations; it facilitates the integration of educational theory and AI, catalyzing pedagogical innovation and practice; and it offers a rigorous scientific foundation for evidence-informed educational policy development and implementation.

Historically, the research on digital education

**Table 8** Major institutions producing core papers on metaverse technologies catalyzing smart learning paradigms

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	University of Copenhagen	6	8.22	1,556	259.33	2020.7
2	Beijing University of Technology	6	8.22	112	18.67	2024.0
3	University of California, Santa Barbara	4	5.48	1,119	279.75	2020.3
4	University of Engineering and Technology Lahore	4	5.48	185	46.25	2023.3
5	Tampere University	3	4.11	1,209	403.00	2020.0
6	The University of Hong Kong	3	4.11	807	269.00	2019.7
7	King Saud University	3	4.11	100	33.33	2024.0
8	Malaysia University of Science and Technology	3	4.11	77	25.67	2023.7
9	University of Turku	2	2.74	1,120	560.00	2019.0
10	East China Normal University	2	2.74	269	134.50	2021.5



**Figure 12** Collaboration network among major institutions producing core papers on metaverse technologies catalyzing smart learning paradigms.

**Table 9** Major countries citing core papers on metaverse technologies catalyzing smart learning paradigms

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	1,590	24.41	2023.1
2	USA	953	14.63	2022.7
3	Spain	496	7.61	2022.6
4	Germany	436	6.69	2022.6
5	UK	423	6.49	2022.8
6	India	351	5.39	2023.3
7	Australia	308	4.73	2022.7
8	Italy	270	4.14	2022.9
9	Malaysia	263	4.04	2023.2
10	Republic of Korea	252	3.87	2023.2

transforming cognition of learning behaviors can be traced back to computer-assisted instruction and educational data mining in the late 20th century. In the early stages, the studies of this field mainly relied on questionnaires and simple log analytics. Subsequently, technological advancements, particularly in biometric sensing, such as eye-tracking and electroencephalography (EEG), enabled the field to extend into the domain of cognitive neuroscience. Since 2020, a notable trend toward interdisciplinary synthesis has emerged, and the application of machine learning algorithms has

enabled real-time identification of complex cognitive states.

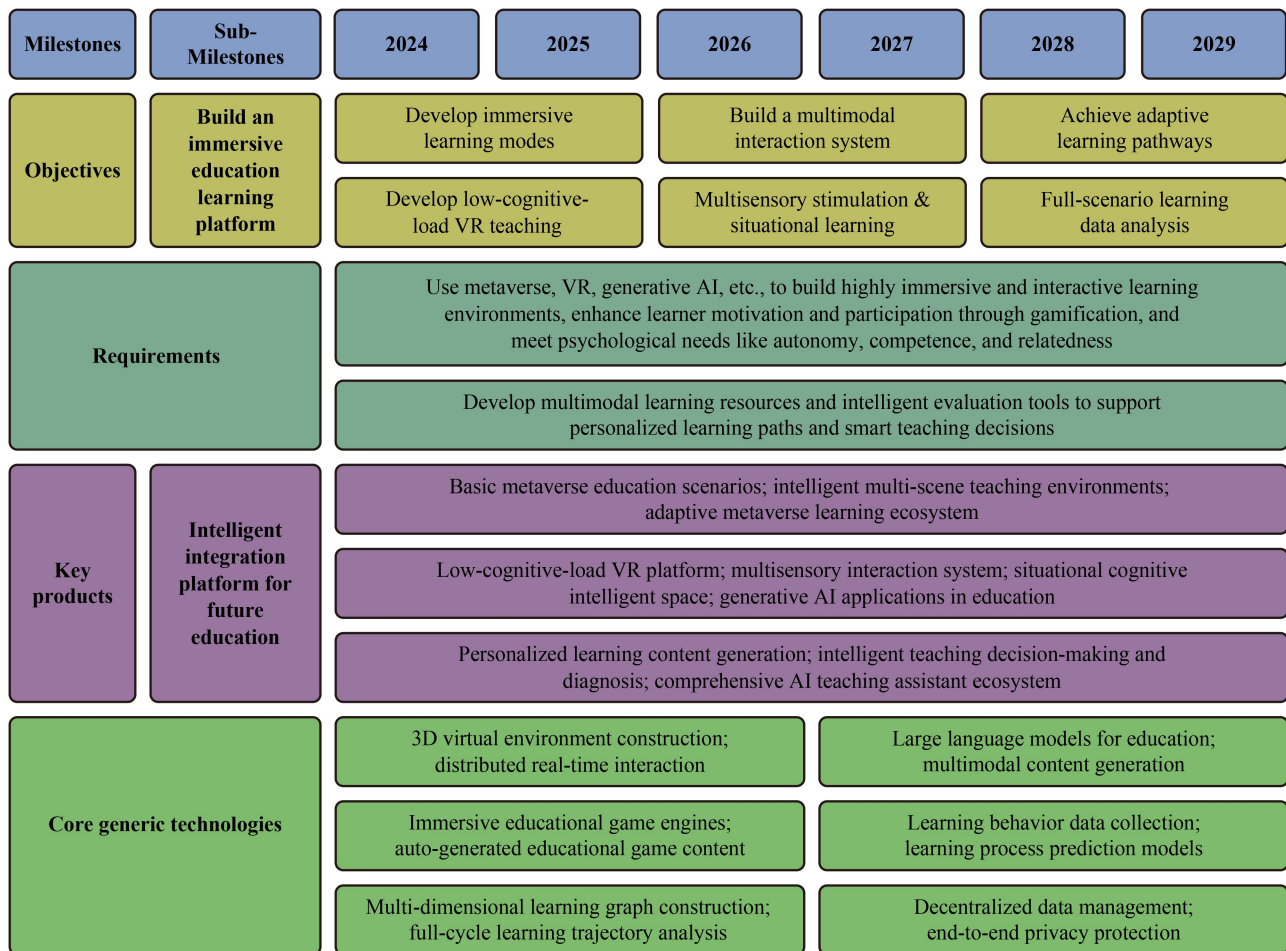
Current research in this field predominantly converges on 3 principal focal areas:

(1) Multimodal data fusion and quantitative behavioral assessment. Through multimodal fusion of physiological, behavioral, and environmental learning data, researchers establish multidimensional representation frameworks capable of systematically capturing and quantitatively assessing learning behaviors.

(2) Learning behavior modeling and cognitive

**Table 10** Major institutions citing core papers on metaverse technologies catalyzing smart learning paradigms

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	Tampere University	106	1.70	2022.2
2	The University of Hong Kong	75	1.20	2022.4
3	The Hong Kong Polytechnic University	60	0.96	2023.1
4	Nanyang Technological University	53	0.85	2022.5
5	University of Copenhagen	49	0.79	2021.8
6	University of Granada	48	0.77	2021.9
7	Taiwan Normal University	48	0.77	2022.5
8	Central China Normal University	48	0.77	2022.9
9	Saint Paul College (USA)	48	0.77	2022.7
10	Symbiosis International University	45	0.72	2023.2



**Figure 13** Developmental roadmap for metaverse technologies catalyzing smart learning paradigms. VR: virtual reality.

state analysis. By utilizing log traces, eye-tracking metrics, and EEG signals, researchers develop mapping models for observing learners' behavioral metrics and cognitive states. Machine learning algorithms are then employed to classify cognitive styles, identify learning engagement levels, and establish robust cognitive ability assessment frameworks.

(3) Affective computing and personalized learning. By leveraging affective computing technologies to analyze learners' emotional states, researchers attempt to develop emotion-aware adaptive learning systems capable of dynamically recommending personalized learning pathways, resources or intervention strategies based on behavioral data.

In the future, the deepening integration of AI, Big Data, and Internet of Things technologies will propel this field toward enhanced real-time processing capacities, personalization, and intelligentization, thereby providing more precise support for educational practices.

In this research hotspot, the top 3 countries by core paper output are China, the Netherlands, and Australia; the top 3 countries by total citations are China, Australia, and Finland; Finland, Spain, and Germany rank highest in terms of average citations per paper (see Table 11). In terms of international collaboration, China and Australia demonstrate the highest degrees (see Figure 14). The top 3 institutions by core paper output are Open Universiteit, Beijing University of Technology, and Wageningen University & Research, while University of Turku, Tampere University, and University of New South Wales lead in average citations per paper (see Table 12). Institutions with the most extensive international research collabora-

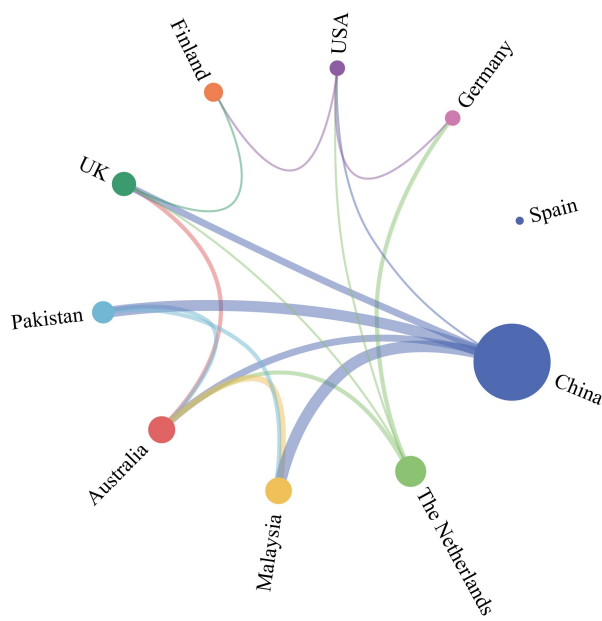
tions include Beijing University of Technology, University of Engineering and Technology Lahore, etc. (see Figure 15). China, the USA, and Germany lead in number of citing papers (see Table 13), while Tampere University, The University of Hong Kong, and The Chinese University of Hong Kong top institutional citing counts (see Table 14). Figure 16 presents the developmental roadmap for digital education transforming cognition of learning behaviors.

### 3.2.4 AI Empowering Personalized Learning Systems: The Future Is Now

Amidst the rapid proliferation of information and AI technologies, AI empowering personalized learning has

**Table 11** Major countries producing core papers on digital education transforming cognition of learning behaviors

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	20	43.48	1,298	64.90	2022.7
2	The Netherlands	8	17.39	981	122.63	2022.5
3	Australia	7	15.22	1,138	162.57	2022.1
4	Malaysia	7	15.22	369	52.71	2022.9
5	UK	6	13.04	233	38.83	2022.8
6	Pakistan	6	13.04	170	28.33	2023.5
7	Finland	5	10.87	1,023	204.60	2021.2
8	Germany	4	8.70	709	177.25	2021.5
9	USA	4	8.70	252	63.00	2021.8
10	Spain	2	4.35	381	190.50	2020.5



**Figure 14** Collaboration network among major countries producing core papers on digital education transforming cognition of learning behaviors.

**Table 12** Major institutions producing core papers on digital education transforming cognition of learning behaviors

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Open Universiteit	6	13.04	248	41.33	2023.0
2	Beijing University of Technology	6	13.04	85	14.17	2024.0
3	Wageningen University & Research	5	10.87	124	24.80	2023.4
4	Universiti Sains Malaysia	4	8.70	307	76.75	2022.3
5	University of Engineering and Technology Lahore	4	8.70	136	34.00	2023.3
6	Tampere University	3	6.52	945	315.00	2020.7
7	University of New South Wales	3	6.52	945	315.00	2020.7
8	The University of Hong Kong	3	6.52	579	193.00	2019.7
9	Zhejiang University of Technology	3	6.52	72	24.00	2023.7
10	University of Turku	2	4.35	890	445.00	2019.5

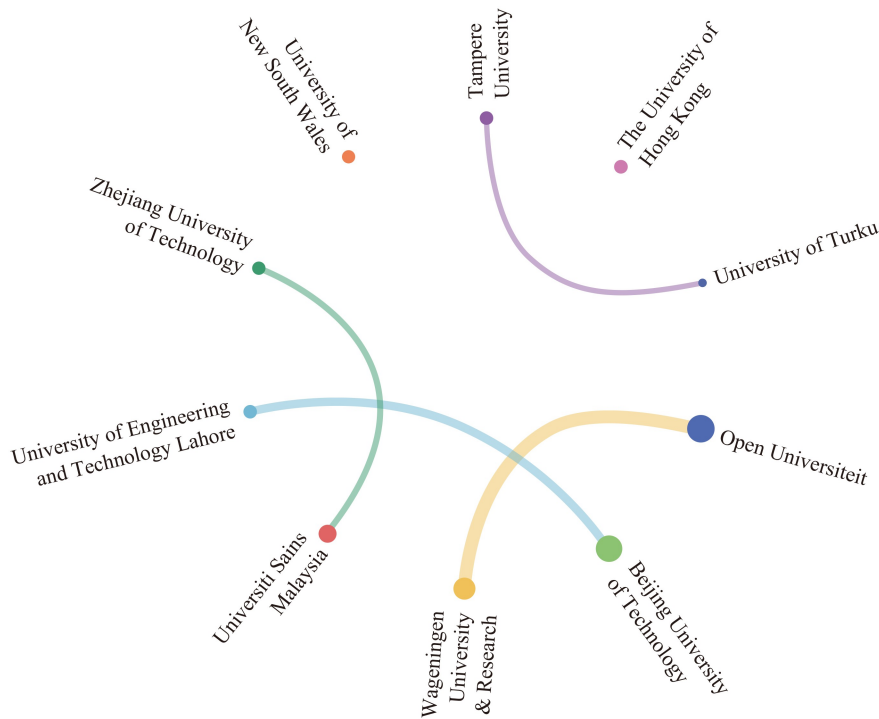
emerged as a pivotal area of inquiry within the broader discourse on educational reform and the development of intelligent learning environments. The construction of personalized pedagogical models underpinned by computational technologies reflects a transformative trajectory in the evolution of educational innovation. These models encompass data-driven adaptive learning systems, real-time interactive intelligent tutoring platforms, and multimodal information processing technologies.

Personalized learning models have gone through 4 distinct developmental stages: traditional classroom-based instruction, characterized by teacher-

led, individual tutoring; rule-based online education platforms, characterized by semi-customized recommendations; algorithm-driven adaptive learning systems, characterized by the implementation of preliminary intelligent content matching; and fully automated, intelligent decision-making and adaptive feedback systems, characterized by GenAI, deep learning, and Big Data.

The studies of this direction predominantly converge on 2 dimensions:

(1) Technological application studies. The existing investigations examine the deployment of core technologies (e.g., speech recognition, NLP, and



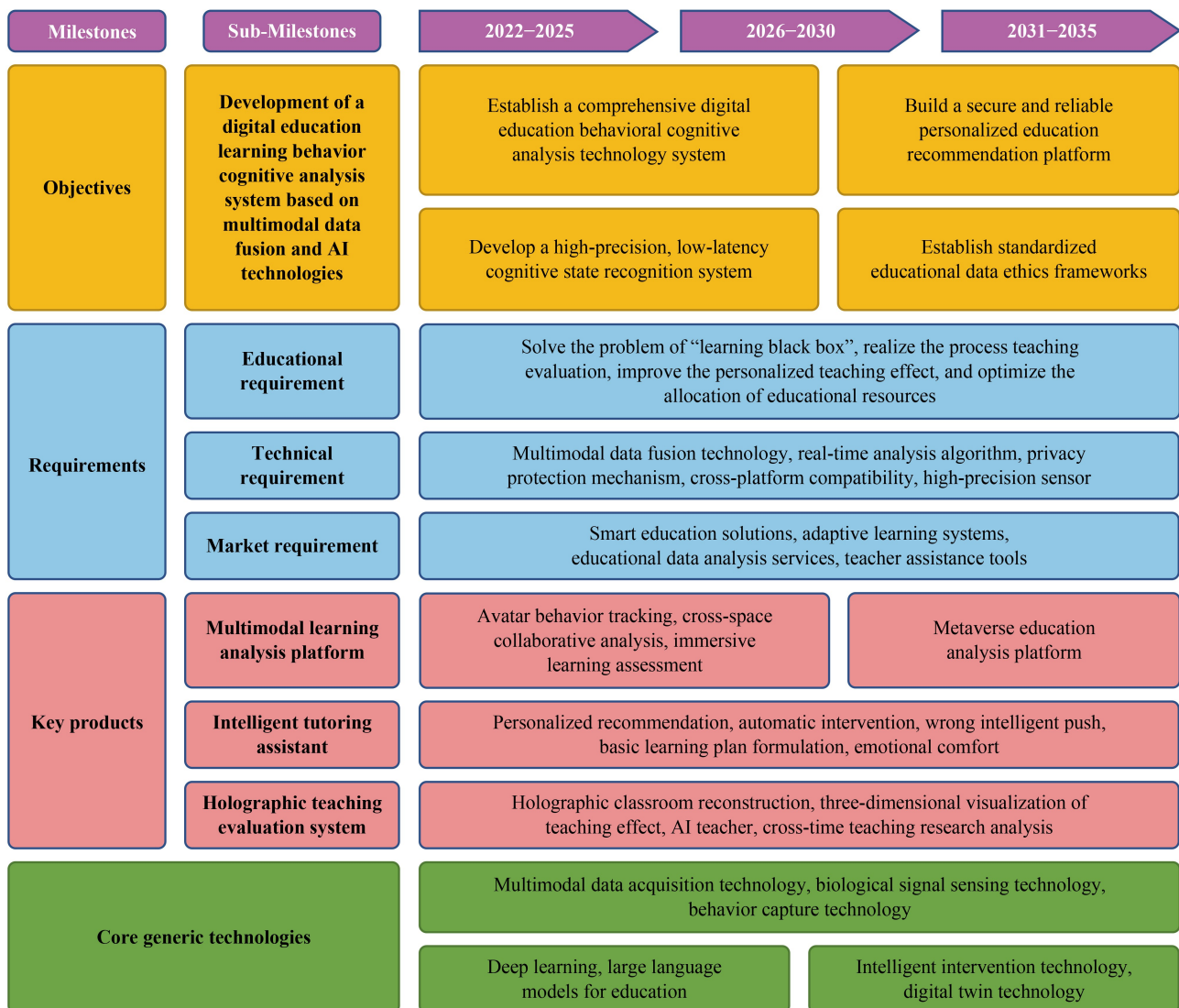
**Figure 15** Collaboration network among major institutions producing core papers on digital education transforming cognition of learning behaviors.

**Table 13** Major countries citing core papers on digital education transforming cognition of learning behaviors

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	1,110	28.94	2022.9
2	USA	574	14.97	2022.5
3	Germany	380	9.91	2022.4
4	Spain	251	6.54	2022.1
5	Australia	249	6.49	2022.4
6	UK	211	5.50	2022.6
7	The Netherlands	176	4.59	2022.4
8	Finland	158	4.12	2022.3
9	Malaysia	134	3.49	2023.0
10	India	131	3.42	2022.9

**Table 14** Major institutions citing core papers on digital education transforming cognition of learning behaviors

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	Tampere University	92	2.40	2022.1
2	The University of Hong Kong	70	1.83	2022.6
3	The Chinese University of Hong Kong	57	1.49	2022.7
4	Central China Normal University	51	1.33	2023.2
5	University of New South Wales	48	1.25	2021.9
6	Erasmus University Rotterdam	46	1.20	2022.1
7	Beijing Normal University	42	1.10	2023.2
8	Taiwan Normal University	37	0.96	2022.3
9	University of Wollongong	37	0.96	2021.9
10	East China Normal University	36	0.94	2023.3



**Figure 16** Developmental roadmap for digital education transforming cognition of learning behaviors.

ffective computing) within online learning platforms. acquisition and responsive, interactive feedback A particular emphasis is placed on real-time data mechanisms.

(2) Systematic management and effectiveness evaluation studies. This line of inquiry explores the integration and enhancement of GenAI technologies for knowledge tracing, personalized learning path optimization, collaborative regulatory frameworks, and instructional design strategies for fully immersive and individualized learning experiences.

Anchored in interdisciplinary synergies among AI, data science, cognitive psychology, and pedagogy, the research fronts of AI-powered personalized learning is advancing toward multidimensional information integration, algorithmic refinement, and dynamic feedback for full-cycle instruction. These developments furnish a robust technological substrate for constructing efficient, intelligent, and resilient smart education ecosystems. Furthermore, they provide strategic impetus for elevating educational quality, ensuring equitable access, and accelerating the

modernization of education systems.

In this research hotspot, the top 3 countries by core paper output are China, the USA, and the UK; the top 3 countries by total citations are China, the USA, and Australia; Australia, the USA, and China rank the highest in terms of average citations per paper (see Table 15). Among the major countries in core paper output, China, the USA, and Australia maintain the most frequent academic partnerships with other countries (see Figure 17). The top 3 institutions by core paper output are Zhejiang University, Universiti Sains Malaysia, and East China Normal University; institutions with the highest average citations per paper are Zhejiang University, The Chinese University of Hong Kong, and Universiti Sains Malaysia (see Table 16). Institutions demonstrating the most frequent international collaborations include Universiti Sains Malaysia, Zhejiang University of Technology, etc. (see

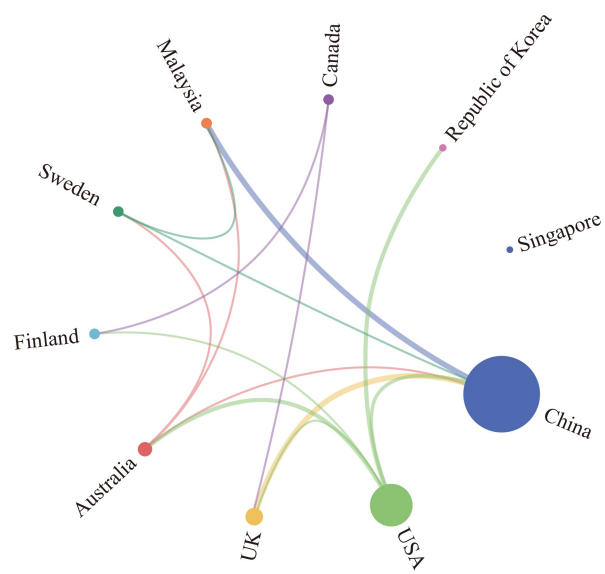
**Table 15** Major countries producing core papers on AI empowering personalized learning: The future is now

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	21	50.00	1,189	56.62	2022.8
2	USA	12	28.57	796	66.33	2022.6
3	UK	5	11.90	162	32.40	2023.2
4	Australia	4	9.52	269	67.25	2023.0
5	Malaysia	3	7.14	142	47.33	2023.3
6	Sweden	3	7.14	114	38.00	2023.7
7	Finland	3	7.14	90	30.00	2023.3
8	Canada	3	7.14	74	24.67	2023.7
9	Republic of Korea	2	4.76	86	43.00	2023.0
10	Singapore	2	4.76	50	25.00	2023.5

Figure 18). The top 3 countries by citing core papers are China, the USA, and Australia (see Table 17). The top 3 institutions of citing core papers are University of Chinese Academy of Sciences, The Chinese University of Hong Kong, and Beijing Normal University (see Table 18). Figure 19 illustrates the developmental roadmap for AI empowering personalized learning: The future is now.

### 3.2.5 Digital Literacy Supporting Teachers' Professional Development

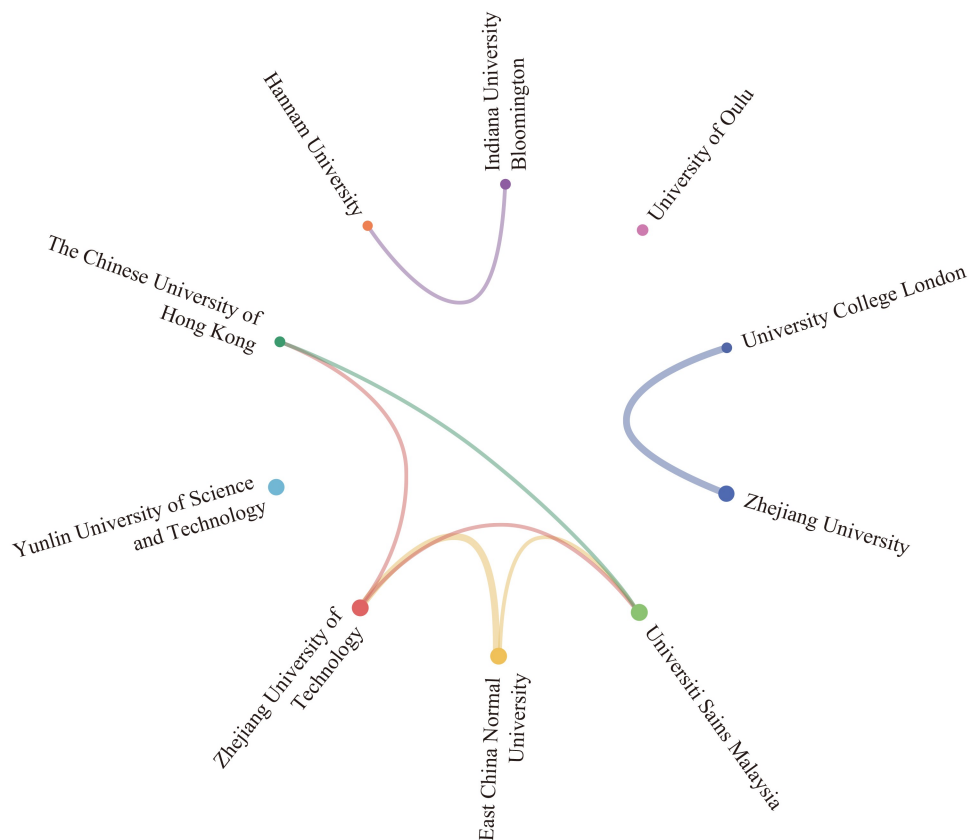
The advancement of teachers' digital literacy is a key pillar in advancing the digital transformation of education, a necessary guarantee for the implementation of educational digital practices, and an important link in the global education reform and development. Since the conceptualization of "digital literacy" in the 1990s, the issue of teachers' digital literacy has garnered increasing scholarly and institutional recognition for its role in refining educational paradigms, enhancing



**Figure 17** Collaboration network among major countries producing core papers on AI empowering personalized learning: The future is now.

**Table 16** Major institutions producing core papers on AI empowering personalized learning: The future is now

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Zhejiang University	3	7.14	171	57.00	2022.7
2	Universiti Sains Malaysia	3	7.14	142	47.33	2023.3
3	East China Normal University	3	7.14	128	42.67	2022.7
4	Zhejiang University of Technology	3	7.14	72	24.00	2023.7
5	Yunlin University of Science and Technology	3	7.14	68	22.67	2023.7
6	The Chinese University of Hong Kong	2	4.76	110	55.00	2023.5
7	Hannam University	2	4.76	86	43.00	2023.1
8	Indiana University Bloomington	2	4.76	86	43.00	2023.1
9	University of Oulu	2	4.76	78	39.00	2023.1
10	University College London	2	4.76	58	29.00	2023.1

**Figure 18** Collaboration network among major institutions producing core papers on AI empowering personalized learning: The future is now.

instructional literacy, and cultivating students' innovative thinking skills. Today, digital literacy has been widely acknowledged as a core professional literacy for educators. The recent integrations of emerging digital technologies, for example, Big Data, AI, and virtual simulation, into educational ecosystems have fundamentally reshaped instructional environments and classroom configurations. Traditional teacher digital literacy models have become inadequate to meet the evolving demands of contemporary and

future-oriented education. Notably, the rapid proliferation of GenAI tools (e.g., ChatGPT and DeepSeek) has not only invigorated the transformation of teachers' core digital literacies but also presented formidable challenges to their capacity for effective application implementation. Therefore, the development of teachers' digital literacy has emerged as a key research front within the broader discourse on educational digitalization.

Contemporary frameworks for digital literacy

**Table 17** Major countries citing core papers on AI empowering personalized learning: The future is now

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	950	48.52	2023.2
2	USA	250	12.77	2023.2
3	Australia	113	5.77	2023.2
4	UK	111	5.67	2023.3
5	Saudi Arabia	85	4.34	2023.4
6	Republic of Korea	78	3.98	2023.2
7	Türkiye	77	3.93	2023.1
8	Malaysia	68	3.47	2023.3
9	Spain	66	3.37	2022.9
10	India	56	2.86	2023.3

**Table 18** Major institutions citing core papers on AI empowering personalized learning: The future is now

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	University of Chinese Academy of Sciences	74	3.78	2022.4
2	The Chinese University of Hong Kong	45	2.30	2023.1
3	Beijing Normal University	43	2.20	2023.0
4	Zhejiang University	42	2.15	2023.3
5	East China Normal University	41	2.09	2023.2
6	Central China Normal University	37	1.89	2023.1
7	The Education University of Hong Kong	31	1.58	2023.4
8	University of Oulu	25	1.28	2023.5
9	South China Normal University	24	1.23	2023.0
10	The University of Hong Kong	21	1.07	2023.3

supporting teachers' professional development typically revolve around five principal dimensions: digital awareness, digital technology knowledge and proficiency, digital application and pedagogical integration, digital ethics and social responsibility, and professional growth and continuous development. Ongoing research concerning the formulation of future literacy benchmarks, capacity-building strategies, and sustainable development pathways is largely structured around these 5 interrelated domains. Relevant research centers on 3 aspects:

(1) Research on teachers' acceptance of digital technology and its influencing factors. The studies of this direction investigate educators' cognitive dispositions, proficiency levels, and practical engagement with digital tools in current teaching contexts. They further identify key factors influencing digital instructional competencies, examine structural mechanisms underlying the digital divide, and propose targeted interventions to mitigate disparities.

(2) Research on the cultivation of teachers' digital literacies. This line of inquiry explores the integration of intelligent technologies (e.g., AI-assisted feedback systems and generative tools) to support

educators in harnessing Big Data and algorithmic insights for instructional optimization, pedagogical innovation, and systemic transformation. Research in this direction primarily concerns the enhancement of teachers' digital consciousness and the construction of practice-oriented competency evaluation systems.

(3) Research on teachers' mental health and adaptability to online teaching in a digitalized teaching environment. This research direction examines the complex manifestations and dynamic fluctuations of teachers' emotional states in specific contexts, evaluates the potential impact of teachers' subjectivity on digital education outcomes, studies the tangible effects and inherent challenges associated with online teaching practices, and explores multidimensional strategies for enhancing teachers' digital pedagogical competence.

In this research hotspot, the USA, Spain, and the UK rank as the top 3 countries by core papers output; Spain, the USA, and the UK maintain leadership, when measured by total citations; the top 3 countries by average citations per paper are Canada, Spain, and Switzerland (see Table 19). The most frequent international research collaborations occur with Germany, the USA, the Netherlands, and Iran (see

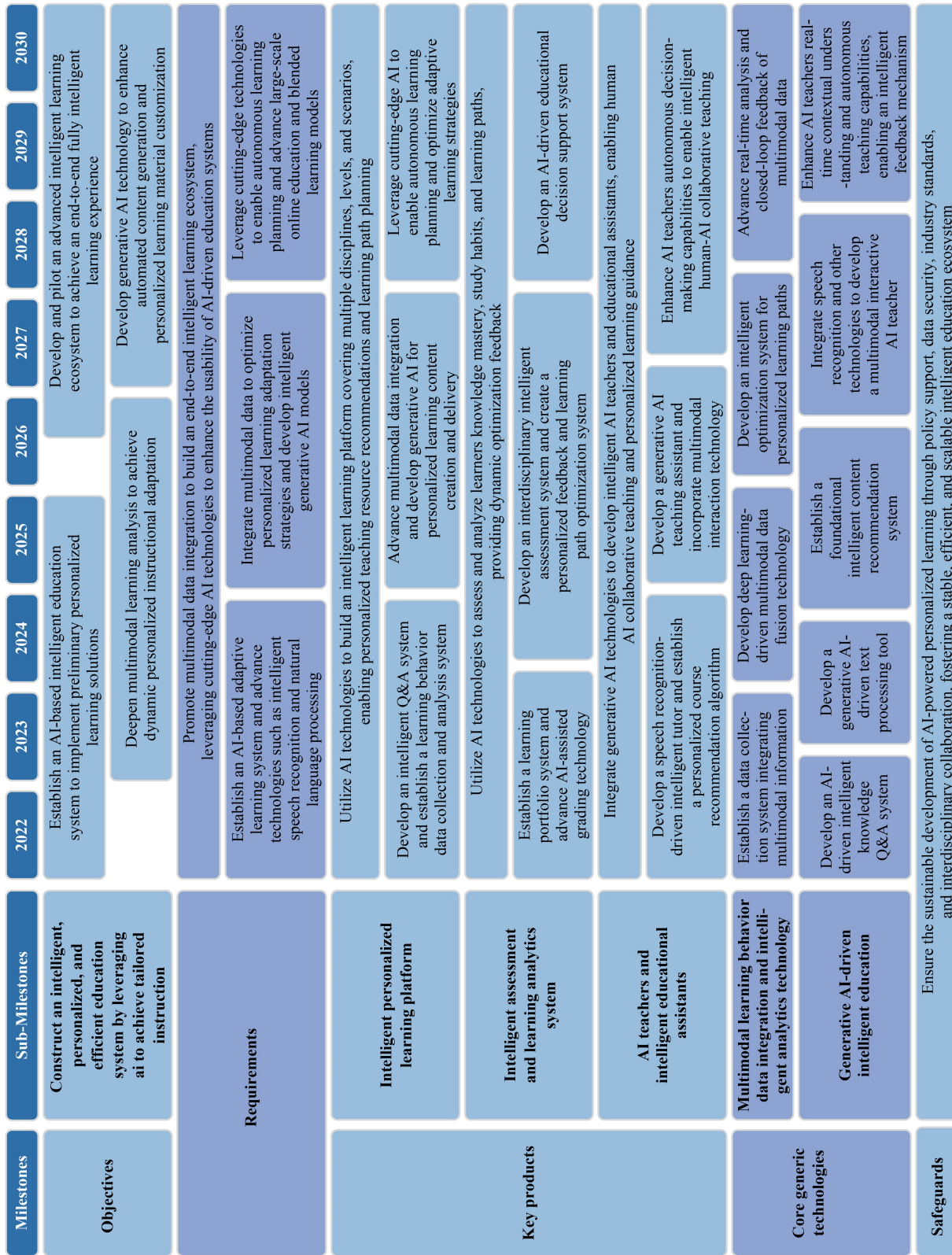
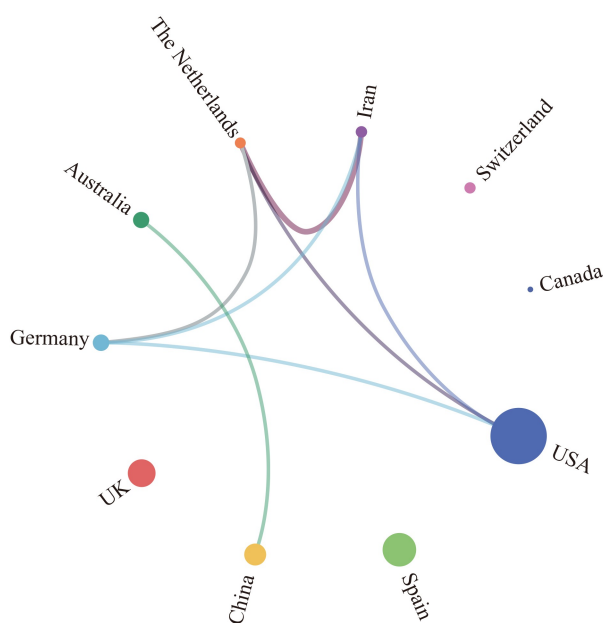


Figure 19 Developmental roadmap for AI empowering personalized learning: The future is now.

**Table 19** Major countries producing core papers on digital literacy supporting teachers’ professional development

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	USA	10	27.03	1,130	113.00	2022.0
2	Spain	6	16.22	1,542	257.00	2020.2
3	UK	5	13.51	1,020	204.00	2020.6
4	China	4	10.81	451	112.75	2021.5
5	Germany	3	8.11	594	198.00	2022.3
6	Australia	3	8.11	485	161.67	2021.0
7	Switzerland	2	5.41	423	211.50	2024.5
8	The Netherlands	2	5.41	45	22.50	2020.5
9	Iran	2	5.41	45	22.50	2024.5
10	Canada	1	2.70	444	444.00	2020.0

Figure 20). The top 3 institutions by core paper output are University of York, York St John University, and University of Granada; the top 3 institutions by average citations per paper are University of Cologne, York St John University, and University of York (see Table 20). Among the major institutions in core paper output, Wageningen University & Research, Ferdowsi University of Mashhad, and Open Universiteit collaborate the most in research (see Figure 21). The top 3 countries by citing core papers are China, the USA, and Spain (see Table 21), while the top 3 institutions are The Education University of Hong Kong, Monash University, and University of Eastern Finland (see Table 22). Figure 22 presents the developmental roadmap for digital literacy supporting teachers’ professional development.



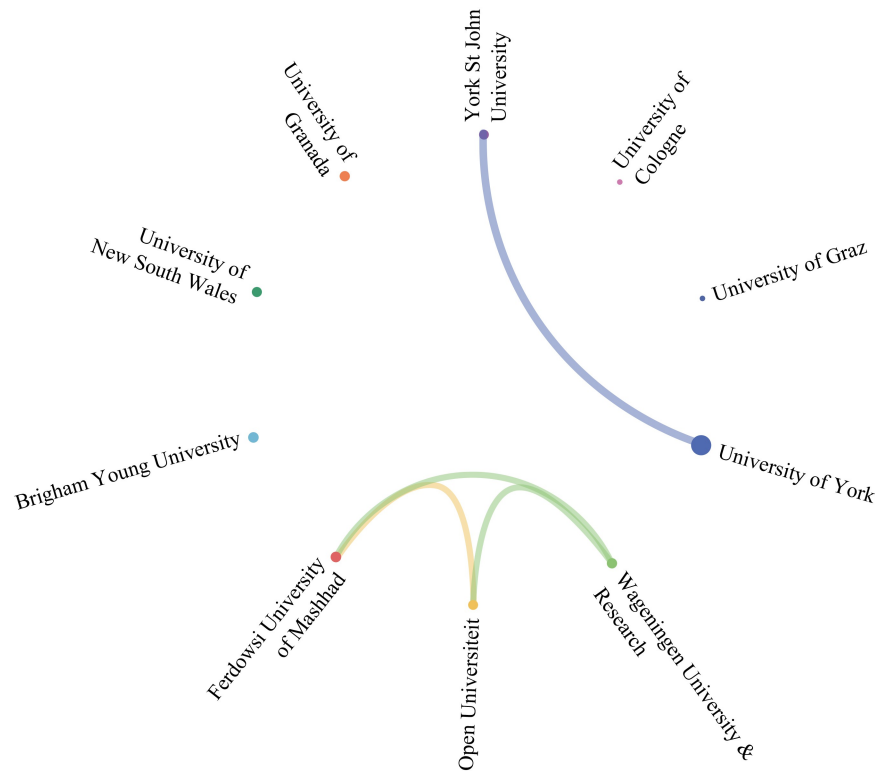
**Figure 20** Collaboration network among major countries producing core papers on digital literacy supporting teachers’ professional development.

**3.2.6 Human–AI Collaboration Reshaping Digital Education Ecosystem**

The evolution of educational paradigms has always been intertwined with societal transformation and technological innovation. From oral transmission in

**Table 20** Major institutions producing core papers on digital literacy supporting teachers’ professional development

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	University of York	4	10.81	839	209.75	2021.0
2	York St John University	2	5.41	430	215.00	2021.0
3	University of Granada	2	5.41	316	158.00	2020.5
4	University of New South Wales	2	5.41	180	90.00	2021.5
5	Brigham Young University	2	5.41	160	80.00	2022.0
6	Wageningen University & Research	2	5.41	45	22.50	2024.5
7	Ferdowsi University of Mashhad	2	5.41	45	22.50	2024.5
8	Open Universiteit	2	5.41	45	22.50	2024.5
9	University of Cologne	1	2.70	519	519.00	2020.0
10	University of Graz	1	2.70	444	444.00	2020.0



**Figure 21** Collaboration network among major institutions producing core papers on digital literacy supporting teachers’ professional development.

**Table 21** Major countries citing core papers on digital literacy supporting teachers’ professional development

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	848	16.76	2022.9
2	USA	765	15.12	2022.8
3	Spain	439	8.67	2022.4
4	UK	316	6.24	2022.7
5	Australia	297	5.87	2022.8
6	Germany	264	5.22	2022.6
7	Türkiye	183	3.62	2022.8
8	Malaysia	155	3.06	2022.9
9	Indonesia	149	2.94	2022.6
10	Saudi Arabia	148	2.92	2022.6

**Table 22** Major institutions citing core papers on digital literacy supporting teachers’ professional development

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	The Education University of Hong Kong	75	1.48	2023.0
2	Monash University	60	1.19	2022.7
3	University of Eastern Finland	45	0.89	2022.8
4	Beijing Normal University	44	0.87	2022.8
5	University College London	38	0.75	2023.0
6	The Chinese University of Hong Kong	35	0.69	2023.3
7	University of New South Wales	33	0.65	2022.7
8	University of Serbia	33	0.65	2022.5
9	University of Helsinki	31	0.61	2022.8
10	Tampere University	31	0.61	2022.9

Milestones	Sub-Milestones	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Objectives	Build a high-quality and professional teaching workforce for the digital age	Leverage digital technology to build an integrated smart education platform for teacher training, teaching, and professional development					Facilitate collaboration among governments, schools, and enterprises to optimize resource allocation, establish a dynamic and fluid sharing network, and break down educational barriers				
		Develop comprehensive digital literacy micro-competency evaluation framework to guide the improvement of teachers' digital literacy					Design intelligent, real-time data collection tools to create an effective and usable digital profile database, laying the foundation for a career diagnosis system				
Requirements		Achieve the digital transformation of teachers to adapt to the development of the digital era and educational innovation, thereby advancing education digitalization									
		Extensively apply digital technologies such as Big Data, cloud computing, virtual reality, and generative AI to drive a holistic transformation of the education ecosystem									
		Integrate digital technologies with quality-oriented education to cultivate high-quality, innovative talents									
Key products	Platform for cultivating, enhancing and developing digital literacy in teacher education careers	Big Data + AI dual-driven teacher training system centered on teachers' digital literacy									
		Interactive intelligent education platform integrating teaching resources, career growth, and digital technology					Comprehensive smart campus upgrade plan covering all levels and types of institutions				
		Multidimensional and holistic teacher competency assessment model		Personalized and diverse career diagnosis system			Digital teacher avatar integrating behavioral, interactive, physiological, and psychological data				
	Interactive and collaborative digital intelligent system	Intelligent teaching collaboration platform enabling cross-urban and cross-regional interactions, based on regional teacher digital communities									
		Government-led, industry-empowered education resource allocation and collaboration platform driven by policy-enterprise intelligence									
Core generic technologies		Digital technologies such as Big Data, cloud computing, virtual reality, digital twins, and AI									
Safeguards		Anticipate future trends in teachers' digital competence development, emphasize the formation of technical and practical capabilities, and build a China-specific digital literacy framework									
		Enhance the overall coordination of educational resources, improve the modern education system, formulate digital education development plans, and actively participate in the global wave of educational digital transformation									

**Figure 22** Developmental roadmap for digital literacy supporting teachers' professional development.

primitive societies to the classroom-based teaching system in the industrial societies, the educational ecosystem has undergone a transition from simplicity to complexity, and from enclosure to openness. The advent of the information society witnessed the rise of online learning as a hallmark of education's digital transformation, wherein technological integration remained largely supplementary without achieving paradigmatic alteration in the inter-subjective relational matrix of educational ecosystems.

In recent years, the rapid proliferation of

GenAI technologies, such as ChatGPT and DeepSeek, has signaled the arrival of an "intelligent digital era" in education—an era characterized by AI's transformation from an auxiliary tool to a brand-new agent in pedagogical scenarios. A novel paradigm of digital education characterized by human-AI symbiosis and communicative rationality is gradually emerging. This marks a fundamental transition from unidimensional linear structures to multidimensional interactive networks in education. This transformation demonstrates dynamic generative and continuous

evolutionary properties.

Research suggests that the construction of this new paradigm of human–AI collaborative digital education is of multidimensional strategic significance in global educational reform. First, this new paradigm integrates technological empowerment and humanistic care, providing more comprehensive and personalized learning support. Second, it transcends geographical barriers in the allocation of educational resources, enabling delivery of high-quality educational resources to remote areas through virtual classrooms and holographic projection technologies. Furthermore, human–AI collaborative education emphasizes synergistic cooperation among teachers, students, and intelligent systems to cultivate learners’ thinking abilities and innovative capacities, addressing future society’s demand for interdisciplinary talents. Third, through dynamic feedback and adaptive regulation mechanisms, this paradigm drives continuous innovation and optimization of educational systems, thereby offering new pathways for digital education transformation and sustainable development of educational ecosystems.

Currently, both scholarly inquiry and practical implementation in the novel models of human–AI collaborative education are advancing rapidly. Globally, policy frameworks increasingly support educational digitalization. For instance, China’s *2024–2035 Master Plan on Building China into a Leading Country in Education* and its National Strategic Action for Digital Education provide institutional guarantees for innovation in this field. Concurrently, breakthroughs in GenAI technologies are providing robust technical foundations for human–AI collaborative education, facilitating a shift from knowledge dissemination to co-construction.

Four key research foci in the novel models of human–AI collaborative education include:

(1) Developing intelligent pedagogical tools, for example, GenAI-powered question-and-answer systems

and speech-recognition chatbots, to enhance learning efficacy through real-time interaction;

(2) Constructing integrated physical–virtual learning environments that create immersive virtual classrooms through metaverse platforms, VR, and holographic projection technologies;

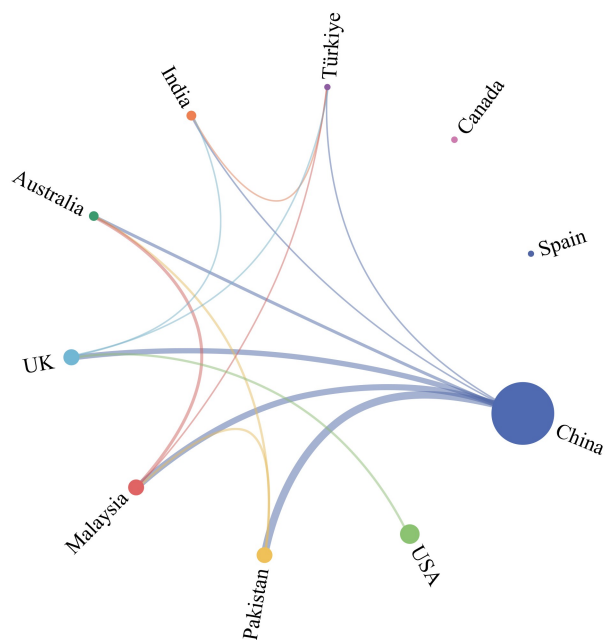
(3) Providing affective learning support by monitoring learners’ emotional states and cognitive loads in real time while establishing cognition–emotion dual-channel support mechanisms via multimodal data analysis and affective computing;

(4) Reconstructing collaborative learning mechanisms through redesigning inquiry-driven instructional models featuring human–AI collaboration where AI serves as a “collaborator” to assist teachers and students in solving complex problems and co-constructing knowledge graphs.

In terms of academic output in this field, China, the USA, and the UK lead in the number of core papers; China, Spain, and the USA top the total citation rankings; Spain, India, and Australia demonstrate the highest average citations per paper (see [Table 23](#)). Among major contributing nations, China, Malaysia, the UK, and Türkiye show the most frequent international collaboration (see [Figure 23](#)). At the institutional level, Beijing University of Technology, East China Normal University, and Zhejiang University of Technology lead in core paper output, whereas Florida State University, Atatürk University, and The Chinese University of Hong Kong achieve the highest average citations per paper (see [Table 24](#)). Beijing University of Technology and Zhejiang University of Technology exhibit particularly strong inter-institutional research collaboration networks (see [Figure 24](#)). Regarding citing impact, China, the USA, and Spain emerge as the leading citing countries (see [Table 25](#)), with The Chinese University of Hong Kong, Zhejiang University, and Beijing Normal University being the most active citing institutions (see [Table 26](#)). [Figure 25](#) presents the developmental roadmap for human–AI collaboration reshaping digital education ecosystem.

**Table 23** Major countries producing core paper on human–AI collaboration reshaping digital education ecosystem

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	19	51.35	768	42.67	2023.3
2	USA	6	16.22	507	84.50	2022.5
3	UK	5	13.51	180	36.00	2023.2
4	Malaysia	5	13.51	139	27.80	2023.8
5	Pakistan	5	13.51	92	18.40	2024.0
6	India	3	8.11	364	121.33	2022.7
7	Australia	3	8.11	259	86.33	2022.7
8	Türkiye	3	8.11	219	73.00	2022.7
9	Spain	2	5.41	710	355.00	2020.5
10	Canada	2	5.41	148	74.00	2022.5



**Figure 23** Collaboration network among major countries producing core papers on human-AI collaboration reshaping digital education ecosystem.

### 3.2.7 Vocational Education Aligning with Smart Technology-Driven Innovation Demands

Research on vocational education aligning with smart technology-driven innovation demands primarily focuses on 3 key aspects:

(1) Curriculum system reconstruction, particularly investigating how intelligent technologies facilitate deep integration between vocational education curricula and industry demands through Big Data analysis of global industry trends and occupational skill requirements, enabling precise curriculum updates while promoting innovative development of digital teaching materials;

(2) Teaching model innovation, mainly examining online-offline blended learning supported by

intelligent instructional platforms that incorporate advanced functionalities such as smart attendance tracking, learning behavior analysis, and real-time interactions adopted by vocational institutions worldwide to enhance precise management of the teaching process and personalized guidance and facilitate intelligent transformation of practice-based training models;

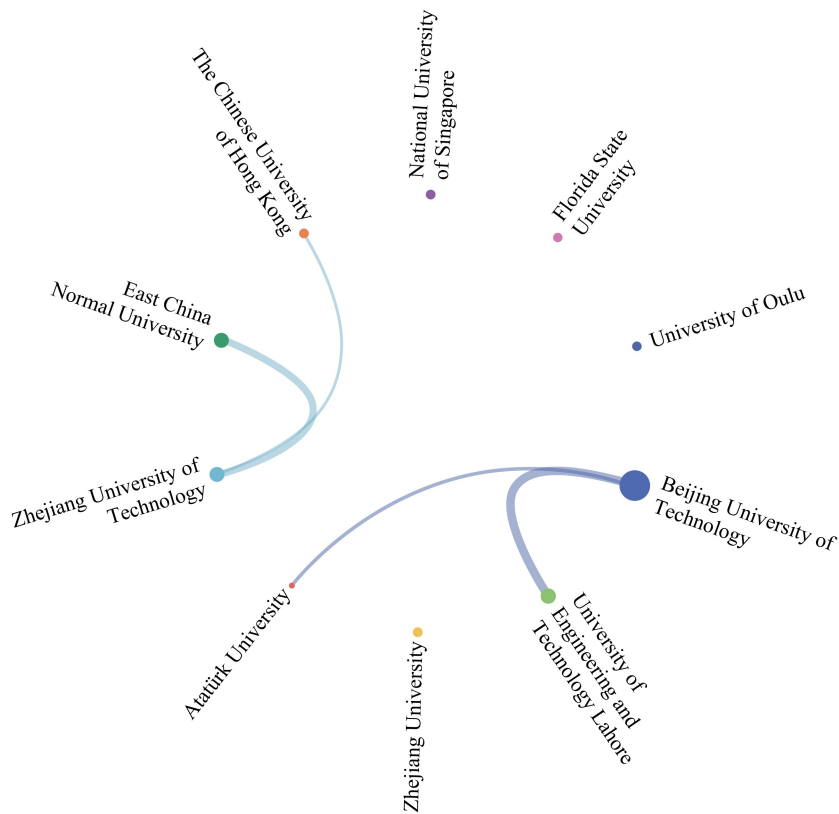
(3) Intelligent transformation of teacher development, focusing on vocational educators’ digital literacies, including digital technology application, digital instructional design, and data-driven assessment skills, while utilizing AI teaching assistants for workload reduction and efficiency enhancement through automated assignment grading and analysis of students’ learning data, thereby allowing teachers to concentrate on instructional design and personalized student guidance.

Looking forward, to achieve equitable and sustainable global development in intelligent vocational education necessitates addressing a constellation of critical challenges. First, focused efforts are needed to mitigate disparities in the intelligent development of vocational institutions across countries and regions, caused by funding shortages and inadequate technological infrastructure in developing nations. Second, critical attention must be paid to data security, privacy protection, and ethical considerations in intelligent technology applications within vocational education.

In terms of scholarly output in this emergent field, the top 3 countries by the number of core papers are China, the USA, and Singapore; the leading countries by total citations are China, Germany, and the USA; countries with the highest average citations per paper include Germany, Sweden, Canada, and Morocco (see Table 27). The nations most actively engaged in international collaborative research are the UK, Singapore, Sweden, Morocco, and Canada (see Figure 26). The top institutions by the number of core papers

**Table 24** Major institutions producing core papers on human-AI collaboration reshaping digital education ecosystem

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Beijing University of Technology	6	16.22	112	18.67	2024.0
2	East China Normal University	3	8.11	101	33.67	2023.3
3	Zhejiang University of Technology	3	8.11	84	28.00	2023.7
4	University of Engineering and Technology Lahore	3	8.11	47	15.67	2024.0
5	Florida State University	2	5.41	253	126.50	2021.5
6	Atatürk University	2	5.41	187	93.50	2022.0
7	The Chinese University of Hong Kong	2	5.41	148	74.00	2024.0
8	University of Oulu	2	5.41	95	47.50	2023.0
9	National University of Singapore	2	5.41	69	34.50	2023.5
10	Zhejiang University	2	5.41	68	34.00	2023.0



**Figure 24** Collaboration network among major institutions producing core papers on human–AI collaboration reshaping digital education ecosystem.

**Table 25** Major countries citing core papers on human–AI collaboration reshaping digital education ecosystem

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	714	24.70	2023.4
2	USA	351	12.14	2023.1
3	Spain	176	6.09	2022.5
4	India	166	5.74	2022.9
5	Saudi Arabia	153	5.29	2023.0
6	UK	145	5.02	2023.3
7	Malaysia	138	4.77	2023.1
8	Türkiye	127	4.39	2023.9
9	Australia	120	4.15	2022.8
10	Germany	90	3.11	2022.8

**Table 26** Major institutions citing core papers on human–AI collaboration reshaping digital education ecosystem

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	The Chinese University of Hong Kong	46	1.59	2023.7
2	Zhejiang University	33	1.14	2023.6
3	Beijing Normal University	31	1.07	2023.4
4	University of Oulu	31	1.07	2023.9
5	Universiti Sains Malaysia	30	1.04	2023.2
6	University College London	28	0.97	2023.2
7	The Education University of Hong Kong	27	0.93	2023.3
8	East China Normal University	27	0.93	2023.5
9	Swinburne University of Technology	25	0.86	2023.9
10	The Hong Kong Polytechnic University	24	0.83	2023.1

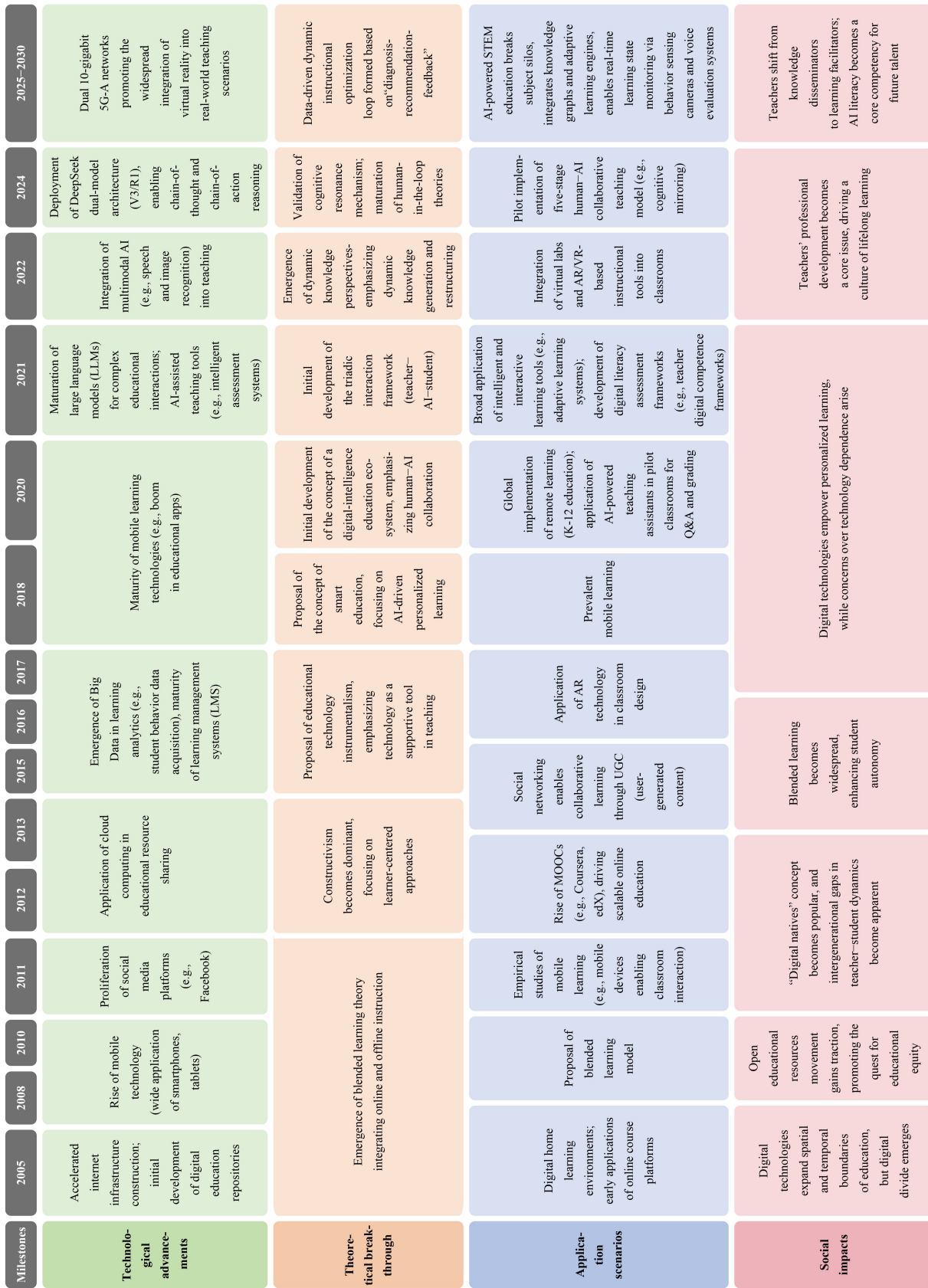
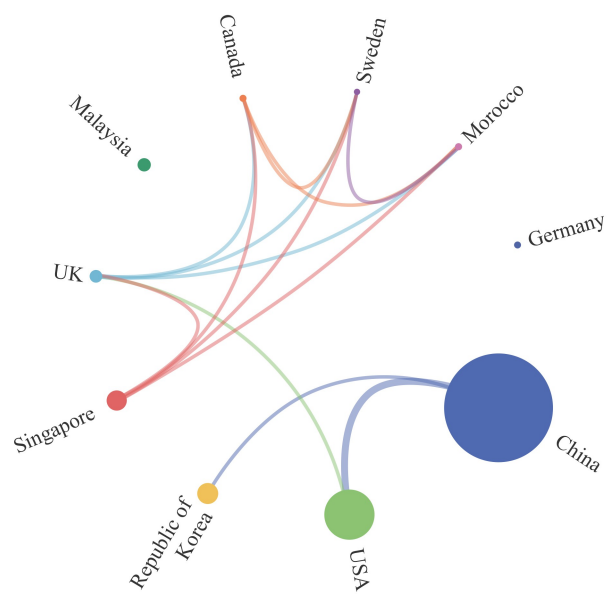


Figure 25 Developmental roadmap for human–AI collaboration reshaping digital education ecosystem. STEM: science, technology, engineering, and mathematics.

**Table 27** Major countries producing core papers on vocational education aligning with smart technology-driven innovation demands

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	15	46.88	1,891	126.07	2022.4
2	USA	7	21.88	867	123.86	2022.9
3	Singapore	3	9.38	343	114.33	2022.0
4	Republic of Korea	3	9.38	240	80.00	2022.7
5	UK	2	6.25	294	147.00	2021.5
6	Malaysia	2	6.25	94	47.00	2022.5
7	Germany	1	3.13	925	925.00	2019.0
8	Sweden	1	3.13	274	274.00	2019.0
9	Canada	1	3.13	274	274.00	2019.0
10	Morocco	1	3.13	274	274.00	2019.0

are Beijing University of Technology, University of Science and Technology Beijing, and University of Illinois Chicago; institutions with the highest average citations per paper are University of Oldenburg, South China University of Technology, and Beijing Normal University (see Table 28). Among leading research institutions, Beijing University of Technology and University of Chinese Academy of Sciences exhibit the highest levels of inter-institutional collaboration (see Figure 27). Regarding citation impact, the top 3 citing countries of core papers are China, the USA, and Spain (see Table 29). The top citing institutions are Beijing University of Technology, Beijing Normal University, and Northeastern University (China) (see Table 30). Figure 28 delineates the developmental roadmap for vocational education aligning with smart technology-driven innovation demands.



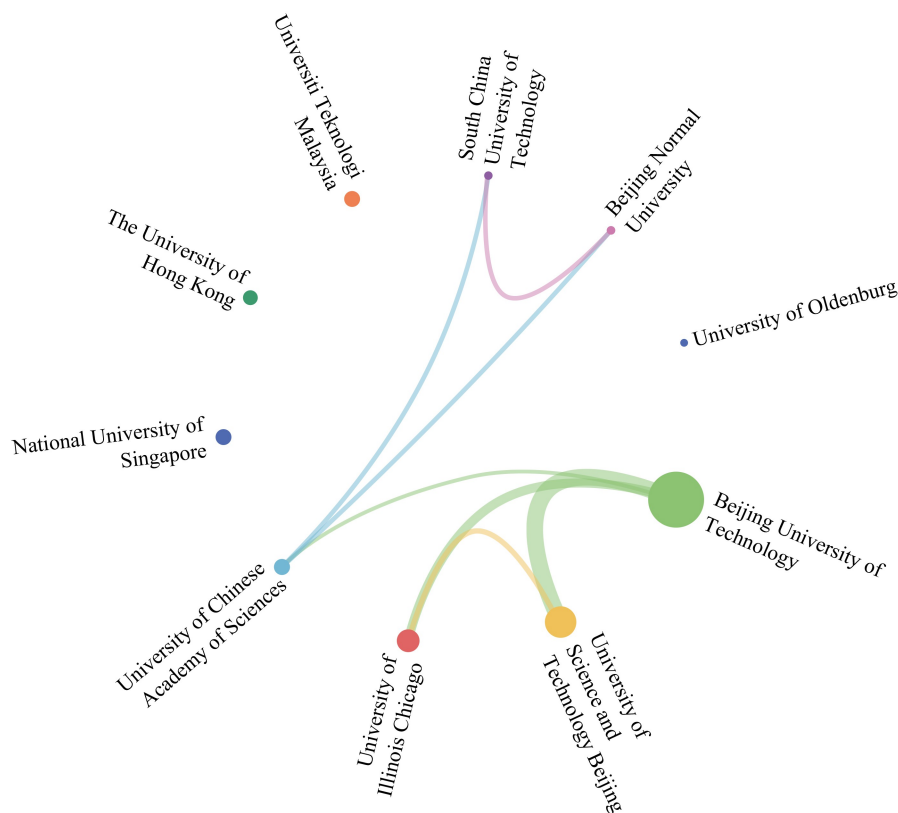
**Figure 26** Collaboration network among major countries producing core papers on vocational education aligning with smart technology-driven innovation demands.

*3.2.8 Global Co-Governance Redefining Ethical Boundaries in Digital Education*

The ethical dimensions of digital education revolve around integrating normative principles into the design

**Table 28** Major institutions producing core papers on vocational education aligning with smart technology-driven innovation demands

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Beijing University of Technology	7	21.88	786	112.29	2022.0
2	University of Science and Technology Beijing	4	12.50	524	131.00	2021.3
3	University of Illinois Chicago	3	9.38	508	169.33	2022.0
4	University of Chinese Academy of Sciences	2	6.25	498	249.00	2021.5
5	The University of Hong Kong	2	6.25	299	149.50	2023.0
6	Universiti Teknologi Malaysia	2	6.25	94	47.00	2022.5
7	National University of Singapore	2	6.25	69	34.50	2023.5
8	University of Oldenburg	1	3.12	925	925.00	2019.0
9	South China University of Technology	1	3.12	378	378.00	2021.0
10	Beijing Normal University	1	3.12	378	378.00	2021.0



**Figure 27** Collaboration network among major institutions producing core papers on vocational education aligning with smart technology-driven innovation demands.

**Table 29** Major countries citing core papers on vocational education aligning with smart technology-driven innovation demands

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	1,375	33.98	2023.1
2	USA	586	14.48	2023.1
3	Spain	217	5.36	2023.0
4	UK	194	4.79	2023.2
5	Australia	160	3.95	2023.1
6	Türkiye	160	3.95	2023.3
7	India	141	3.48	2023.6
8	Saudi Arabia	134	3.31	2023.5
9	Germany	134	3.31	2023.2
10	Republic of Korea	113	2.79	2023.3

and operation of digital learning environments. The overarching objective is to foster a balanced synergy between technological innovation and ethical integrity, while safeguarding core values such as equity and justice, privacy protection, and information security. Currently, as internet technologies have progressively permeated the educational landscape, facilitating the expansion of distance learning and online platforms, ethical dilemmas in digital education have garnered increasing scholarly and policy attention. Concerns

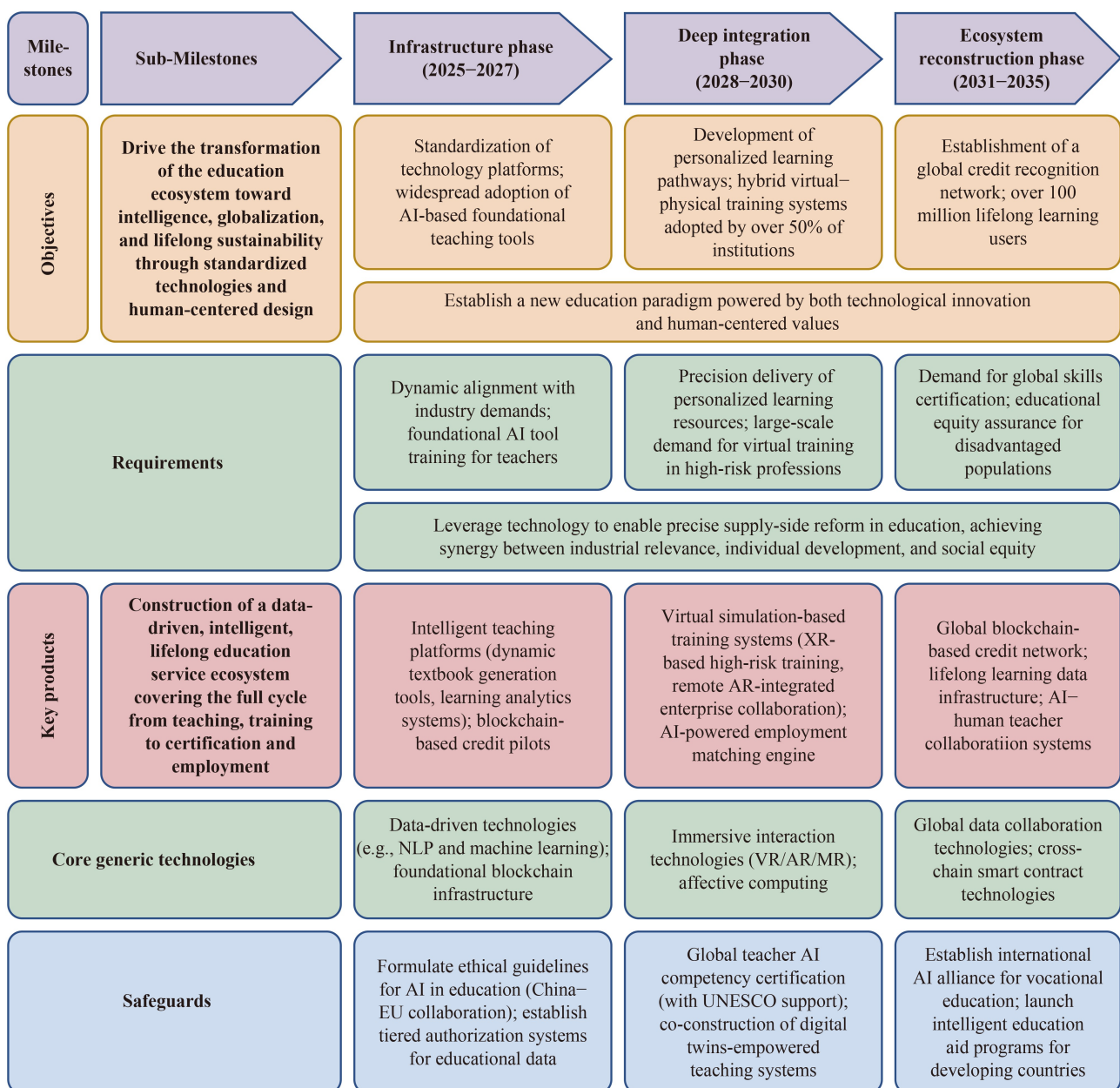
over equitable access to learning opportunities and the protection of personal data have underscored the urgent imperative to construct a universally applicable framework for ethical co-governance in digital education.

Contemporary research on the ethical principles of digital education predominantly focuses on 4 key domains:

(1) The pathways to achieving equitable access to digital educational resources, which examines

**Table 30** Major institutions citing core papers on vocational education aligning with smart technology-driven innovation demands

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	Beijing University of Technology	130	3.21	2022.8
2	Beijing Normal University	71	1.75	2022.8
3	Northeastern University (China)	65	1.61	2022.8
4	Guangdong University of Technology	60	1.48	2022.5
5	The Education University of Hong Kong	56	1.38	2023.1
6	The University of Hong Kong	56	1.38	2023.1
7	Florida State University	48	1.19	2023.2
8	University of Illinois Chicago	45	1.11	2022.6
9	University of Science and Technology Beijing	44	1.09	2022.2
10	University of Chinese Academy of Sciences	43	1.06	2022.4



**Figure 28** Developmental roadmap for vocational education aligning with smart technology-driven innovation demands.

practical strategies for bridging the digital divide amid the dual drivers of accelerating digital transformation and the diversification of educational resource access channels.

(2) The ethical co-governance mechanisms for technological applications, which address systemic risks such as algorithmic bias and “black-box decision-making” inherent in deploying AI and other emerging technologies in education. The aim is to prevent polarization between “digital privilege” and “digital poverty” while establishing comprehensive ethical review mechanisms encompassing the full lifecycle of digital education.

(3) The optimization of rights and responsibilities among stakeholders in digital education, safeguarding data privacy, information security, and distinct ethical responsibilities borne by different actors. This includes addressing issues such as the extensive collection of personal data from students and teachers,

and protecting labor rights and mental well-being of involved parties.

(4) The international coordination of digital education ethics, which requires addressing such issues as cross-border data flows, privacy protection, intellectual property rights, and algorithmic transparency in digital education. This involves exploring co-governance pathways that reconcile regional differences with global consensus, with the ultimate goal of establishing a tiered and dynamically balanced global coordination framework led by representative international organizations such as the United Nations.

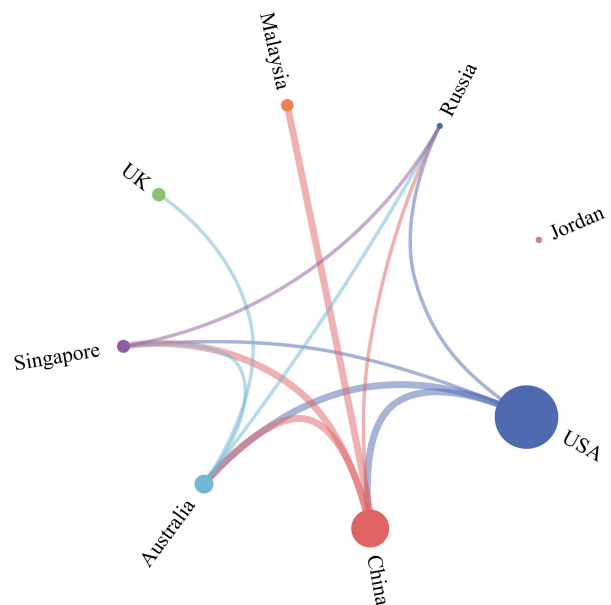
Looking forward, the future development of digital education ethics will prioritize 3 core objectives: advancing educational equity, reinforcing data privacy protections, and optimizing technological deployment. Against the backdrop of relentless technological advancement, ethical principles of digital education

**Table 31** Major countries producing core papers on global co-governance redefining ethical boundaries in digital education

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	USA	10	58.82	1,567	156.70	2023.0
2	China	6	35.29	1,527	254.50	2022.3
3	Australia	3	17.65	1,304	434.67	2021.7
4	Singapore	2	11.76	1,301	650.50	2020.5
5	UK	2	11.76	182	91.00	2023.0
6	Malaysia	2	11.76	62	31.00	2023.5
7	Russia	1	5.88	1,098	1,098.00	2020.0
8	Jordan	1	5.88	63	63.00	2023.0

must undergo iterative refinement to address emerging challenges, thereby ensuring the harmonious co-evolution of education and technology.

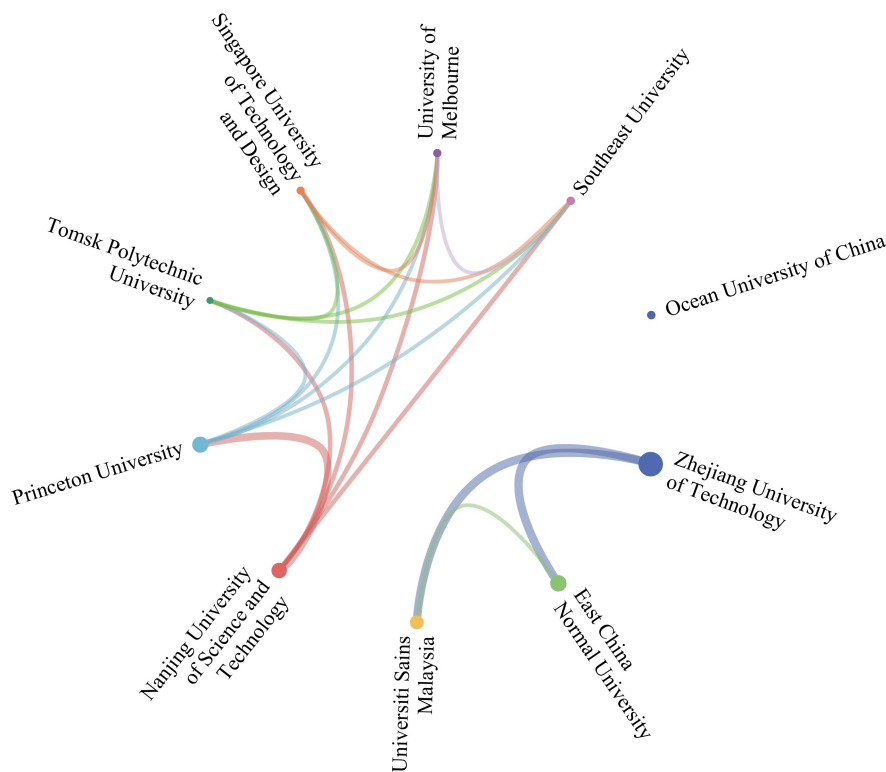
With respect to research output in this field, the top 3 countries by number of core papers are the USA, China, and Australia; these same countries also lead in total citation counts; the highest average citations per paper are observed in Russia, Singapore, and Australia (see Table 31). The countries most actively involved in international research collaborations are China and Australia (see Figure 29). The top institutions by the number of core papers include Zhejiang University of Technology, Princeton University, and Nanjing University of Science and Technology; institutions with the highest average citations per paper are University of Melbourne, Southeast University, Tomsk Polytechnic University, and Singapore University of Technology and Design (see Table 32). Leading collaborative institutions include Nanjing University of Science and Technology, Princeton University, Tomsk Polytechnic University, and Singapore University of Technology and Design, University of Melbourne, and Southeast University (see Figure 30). In terms of citation impact,



**Figure 29** Collaboration network among major countries producing core papers on global co-governance redefining ethical boundaries in digital education.

**Table 32** Major institutions producing core papers on global co-governance redefining ethical boundaries in digital education

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Zhejiang University of Technology	3	17.65	84	28.00	2023.7
2	Princeton University	2	11.76	1,240	620.00	2021.0
3	Nanjing University of Science and Technology	2	11.76	1,240	620.00	2023.5
4	Universiti Sains Malaysia	2	11.76	62	31.00	2023.5
5	East China Normal University	2	11.76	57	28.50	2020.0
6	University of Melbourne	1	5.88	1,098	1,098.00	2020.0
7	Southeast University	1	5.88	1,098	1,098.00	2020.0
8	Tomsk Polytechnic University	1	5.88	1,098	1,098.00	2020.0
9	Singapore University of Technology and Design	1	5.88	1,098	1,098.00	2020.0
10	Ocean University of China	1	5.88	203	203.00	2021.0



**Figure 30** Collaboration network among major institutions producing core papers on global co-governance redefining ethical boundaries in digital education.

the top citing countries are China, the USA, and Australia (see Table 33). The leading citing institutions are Shanghai Jiao Tong University, Nanyang Technological University, and Nanjing University of Science and Technology (see Table 34). Figure 31 outlines the strategic roadmap for global co-governance redefining ethical boundaries in digital education.

### 3.2.9 Digital Education Bridging Regional Gaps in the Balanced Development

Achieving educational equity and regionally balanced

development constitutes a pressing global challenge. Digital education provides novel technological solutions, innovative methodologies, and transformative approaches to address this issue, making research on its regionally balanced development an emerging academic priority.

The primary objectives of this research domain include:

- (1) Promoting precision teaching and personalized learning through AI technologies, and achieving equitable sharing of high-quality educational resources via enhanced application of digital education platforms;

**Table 33** Major countries citing core papers on global co-governance redefining ethical boundaries in digital education

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	831	48.40	2023.4
2	USA	401	23.35	2023.2
3	Australia	169	9.84	2023.1
4	UK	119	6.93	2023.3
5	India	96	5.59	2023.4
6	Canada	81	4.72	2022.9
7	Republic of Korea	80	4.66	2023.0
8	Singapore	74	4.31	2023.3
9	Japan	60	3.49	2023.1
10	Saudi Arabia	51	2.97	2023.7

**Table 34** Major institutions citing core papers on global co-governance redefining ethical boundaries in digital education

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	Shanghai Jiao Tong University	48	3.07	2023.1
2	Nanyang Technological University	43	2.75	2023.1
3	Nanjing University of Science and Technology	39	2.50	2022.6
4	Xidian University	38	2.43	2023.1
5	University of Technology Sydney	38	2.43	2022.9
6	Tsinghua University	35	2.24	2023.1
7	Zhejiang University	33	2.11	2023.3
8	Southeast University	33	2.11	2023.3
9	Chinese Academy of Sciences	32	2.05	2022.9
10	University of Electronic Science and Technology of China	31	1.98	2023.1

(2) Improving resource co-construction/sharing and collaboration mechanisms to build in-depth cooperative frameworks for interconnected educational resources across nations and regions;

(3) Enhancing teachers' digital literacies to advance educational equity.

The current research focuses primarily on 5 key areas:

(1) Balanced development of digital education infrastructure, investigating best practices in digital infrastructure development across nations and regions while exploring context-specific implementation pathways tailored to diverse geographic, administrative, and educational contexts;

(2) Digital education resource-sharing mechanisms, examining strategies for cross-regional course resource circulation and deep integration of high-quality digital education platforms to enable equitable allocation of premium educational resources;

(3) Teacher collaboration and capacity

building, exploring peer-support systems and professional development frameworks for educators across regions and proficiency levels;

(4) Cross-regional collaborative development, leveraging digital technologies to build educational communities, mitigate regional resource disparities, and promote sustainable models for educational development in the digital era;

(5) Balanced and sustainable growth of digital education, addressing global divides such as North–South disparities and developmental gaps between developed and underdeveloped regions.

In terms of research output in this emerging field, the top 3 countries by number of core papers are China, Malaysia, and Spain; the leading countries by total citations are China, Spain, and India; the highest average citations per paper are observed in Spain, India, and the Sultanate of Oman (see Table 35). Among the major countries producing core papers, Malaysia exhibits the highest frequency of international

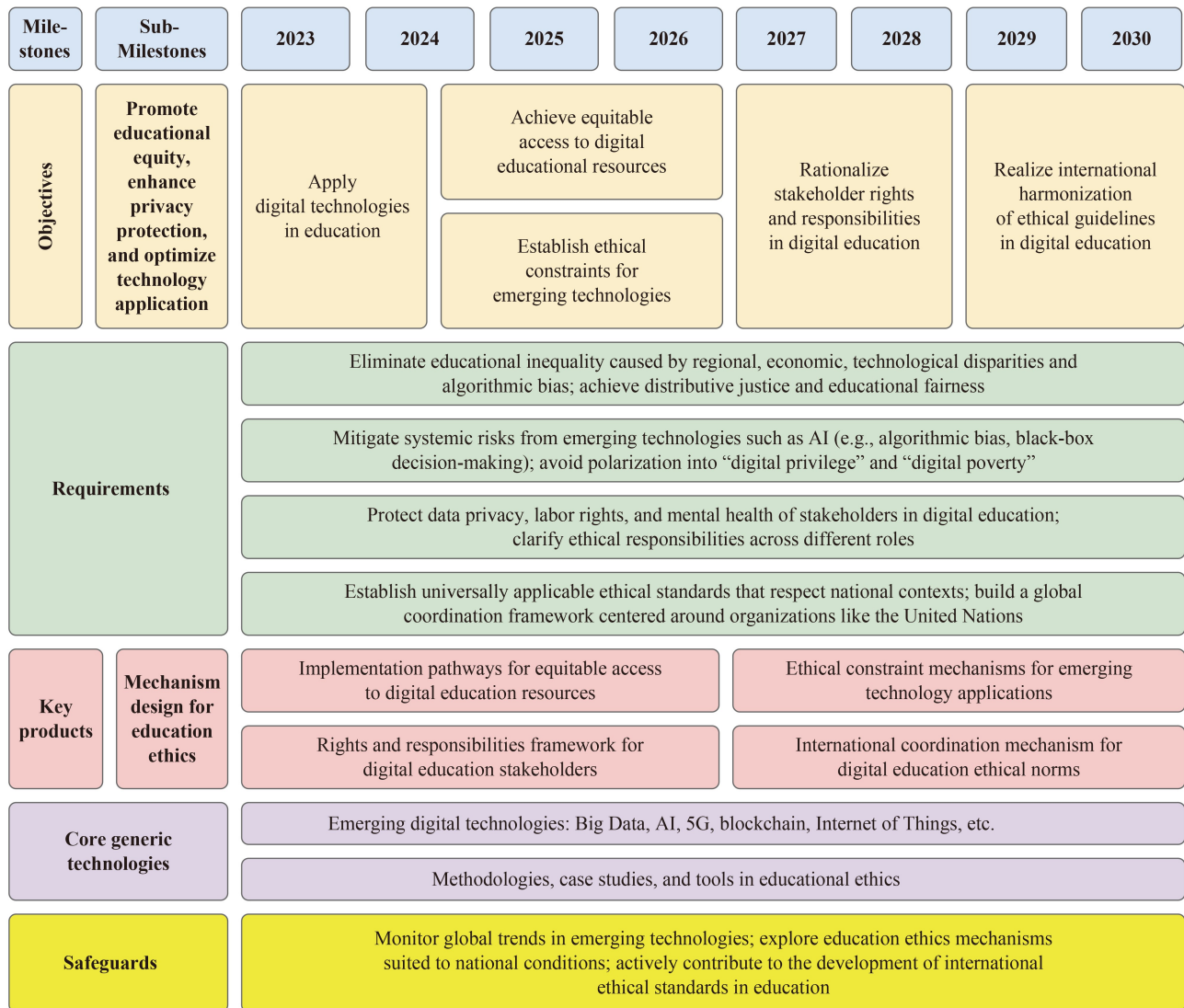


Figure 31 Developmental roadmap for global co-governance redefining ethical boundaries in digital education.

Table 35 Major countries producing core paper on digital education bridging regional gaps in the balanced development

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	China	4	44.44	359	89.75	2022.8
2	Malaysia	3	33.33	296	98.67	2022.0
3	Spain	1	11.11	346	346.00	2020.0
4	India	1	11.11	328	328.00	2020.0
5	The Sultanate of Oman	1	11.11	234	234.00	2019.0
6	USA	1	11.11	97	97.00	2022.0
7	Canada	1	11.11	85	85.00	2022.0

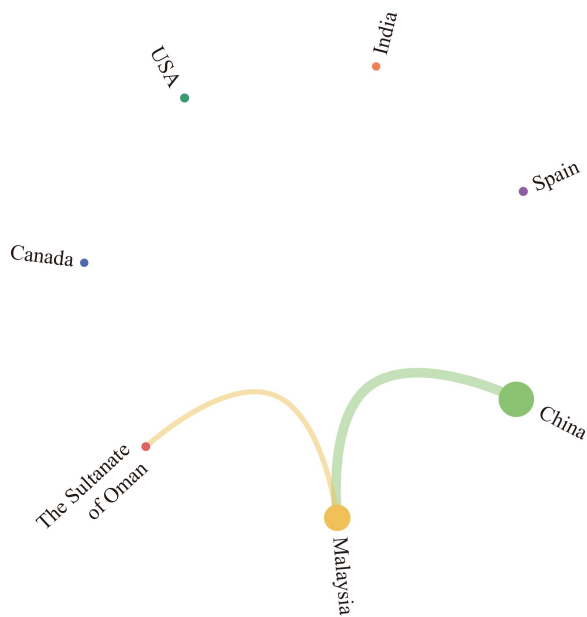
collaboration (see Figure 32). The top institutions by number of core papers are Zhejiang University of Technology, Universiti Sains Malaysia, and East China Normal University; institutions with the highest average

citations per publication include University of Córdoba, Jawaharlal Nehru University, and University of Gour Banga (see Table 36). With respect to institutional collaboration, the most active institution is Universiti

Sains Malaysia (see Figure 33). In terms of citing metrics, the top citing countries are China, the USA, and India (see Table 37). The top citing institutions include East China Normal University, Universiti Sains Malaysia, and Zhejiang University of Technology (see Table 38). Figure 34 delineates the developmental roadmap for digital education bridging regional gaps in the balanced development.

### 3.2.10 Data Driving Intelligent Decision-Making Across the Entire Teaching Process

The integration of AI with digital education has given



**Figure 32** Collaboration network among major countries producing core papers on digital education bridging regional gaps in the balanced development.

rise to data driving intelligent decision-making across the entire teaching process, utilizing multimodal data collection, analysis, and application to enhance evidence-based instructional decision-making capabilities. During the 1980s, the initial use of educational assessment data enabled macro-level policymaking. In the early 21st century, data-driven practices gradually extended into classroom settings, though mainly as localized interventions. With recent breakthroughs in AI algorithms and multimodal data analytics, data-driven instructional decision-making has evolved to encompass the full cycle of education, transitioning from technical validation to large-scale implementation. Current research focuses on achieving deep integration between technological innovations and educational practices.

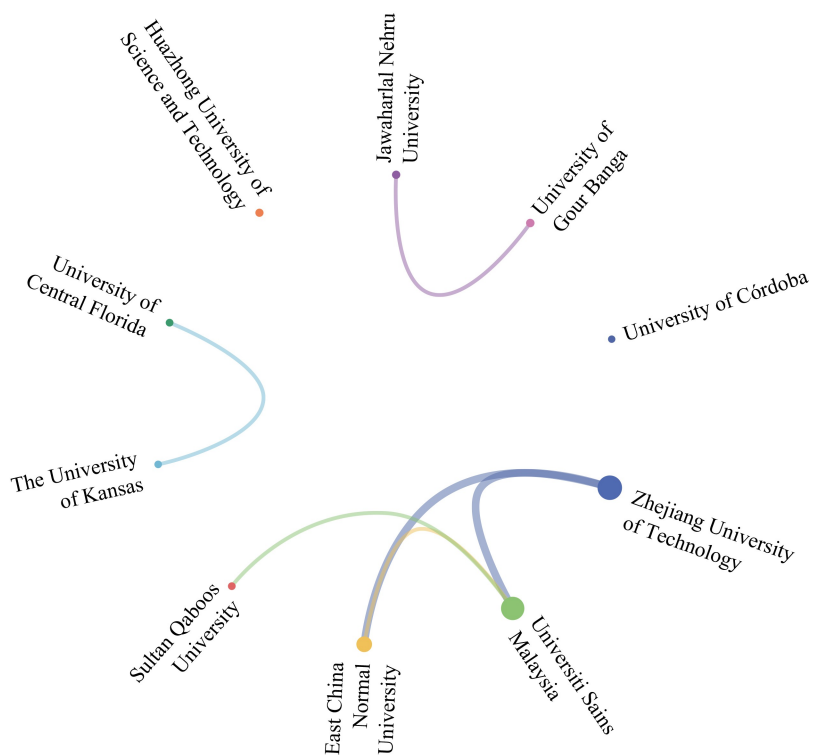
The overarching objective of data-driven intelligent decision-making across the entire teaching process is to foster a more precise and adaptive educational environment. By leveraging real-time behavioral, emotional, and cognitive data, educators are empowered to transcend traditional intuition-based practices and implement personalized, evidence-based interventions. At a broader level, education administrators can harness aggregated data to refine resource distribution strategies, thereby contributing to both improved quality and equity in education.

Current research in this domain primarily focuses on 4 key directions:

- (1) Decision support based on multimodal data integration and intelligent analysis, such as computer vision-assisted sports movement evaluation, or the analysis of correlations between EEG signals and academic performance;
- (2) Innovative integration of decision models with educational theories, such as combining Bloom’s

**Table 36** Major institutions producing core papers on digital education bridging regional gaps in the balanced development

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Zhejiang University of Technology	3	33.33	84	28.00	2023.7
2	Universiti Sains Malaysia	3	33.33	296	98.67	2022.0
3	East China Normal University	2	22.22	57	28.50	2023.5
4	University of Córdoba	1	11.11	346	346.00	2020.0
5	Jawaharlal Nehru University	1	11.11	328	328.00	2020.0
6	University of Gour Banga	1	11.11	328	328.00	2020.0
7	Huazhong University of Science and Technology	1	11.11	275	275.00	2020.0
8	Sultan Qaboos University	1	11.11	234	234.00	2019.0
9	University of Central Florida	1	11.11	97	97.00	2022.0
10	The University of Kansas	1	11.11	97	97.00	2022.0



**Figure 33** Collaboration network among major institutions producing core papers on digital education bridging regional gaps in the balanced development.

**Table 37** Major countries citing core papers on digital education bridging regional gaps in the balanced development

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	301	22.63	2022.7
2	USA	147	11.05	2022.3
3	India	103	7.74	2022.2
4	Saudi Arabia	91	6.84	2022.1
5	Spain	81	6.09	2022.0
6	Malaysia	78	5.86	2022.4
7	UK	62	4.66	2022.3
8	Australia	53	3.98	2022.6
9	Germany	52	3.91	2022.6
10	Canada	36	2.71	2022.4

**Table 38** Major institutions citing core papers on digital education bridging regional gaps in the balanced development

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	East China Normal University	22	1.75	2023.7
2	Universiti Sains Malaysia	20	1.59	2022.5
3	Zhejiang University of Technology	17	1.35	2024.1
4	University of Eastern Finland	13	1.04	2022.5
5	The Hong Kong Polytechnic University	12	0.96	2022.3
6	The Chinese University of Hong Kong	12	0.96	2023.8
7	Zhejiang University	12	0.96	2022.8
8	Monash University	11	0.88	2023.0
9	Huazhong University of Science and Technology	10	0.80	2021.5
10	Kyoto University	10	0.80	2022.0

Milestones	Sub-Milestones	2023	2025	2027	2029	2031	2033
Objectives	Balanced regional development of digital education	Digital education infrastructure network			Cross-regional intelligent matching mechanism for high-quality educational resources		
		Schools in developed and underdeveloped regions partnership and assistance model		Urban–rural educational community with cloud-based teaching and research system		Emergency response system for digital education	
Requirements	Strategic requirements	Promoting balanced regional development of digital education is a key strategy to address demographic structural changes					
	Talent development requirements	Promoting balanced regional development of digital education is the foundation for cultivating localized digital talent					
	Industrial requirements	Promoting balanced regional development of digital education helps resolve the imbalance of local surplus and overall scarcity in high-quality educational resources					
Key products	Communication infrastructure	Education networks		Lightweight, user-friendly teaching terminals			
	Teaching and research systems	Platforms for digital textbooks and teaching resources		Online teaching assessment systems		Online teacher training systems	
		Virtual laboratories		Emergency response platforms for the educational sector			
Core generic technologies	Infrastructure	Network coverage and communication based on 5G/6G, low-latency networks, satellite internet, edge computing, and Internet of Things					
		Cloud computing and distributed storage ensuring efficient storage and rapid distribution of educational resources					
	Teaching interaction and adaptive technologies	Personalized learning based on machine learning and affective computing			Real-world classroom simulation based on virtual reality and real-time communication		
	Digital educational resource creation and sharing	Intelligent content generation based on natural language processing, generative AI, and multimodal resource development					
Resource sharing and copyright protection based on blockchain and open educational resources (OER) platforms							

Figure 34 Developmental roadmap for digital education bridging regional gaps in the balanced development.

taxonomy with reinforcement learning to design adaptive learning pathways, or constructing subject-specific competence diagnosis models using knowledge graph methodologies;

(3) Mechanisms for teachers’ data literacy development, including pre-service data literacy curriculum design and in-service data practice community building;

(4) Establishment of educational data ethics

and governance frameworks, covering data anonymization, algorithmic fairness verification, and reliability evaluation of human–AI collaborative decision-making.

Typical application scenarios, including intelligent lesson planning systems that recommend instructional materials based on historical data, real-time classroom dashboards that enable dynamic adjustments to teaching pace, and personalized assignment grading and learning path planning, all

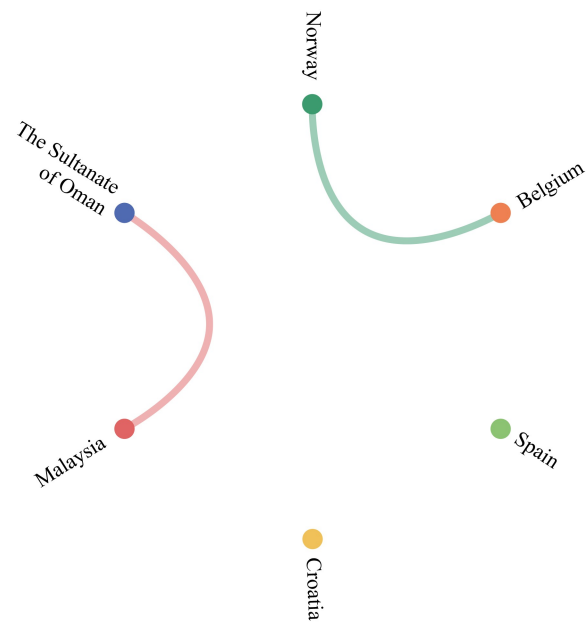
**Table 39** Major countries producing core papers on data driving intelligent decision-making across the entire teaching process

No.	Country	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Belgium	1	25	760	760	2019.0
2	Norway	1	25	760	760	2019.0
3	Croatia	1	25	427	427	2019.0
4	Spain	1	25	346	346	2019.0
5	Malaysia	1	25	234	234	2019.0
6	The Sultanate of Oman	1	25	234	234	2019.0

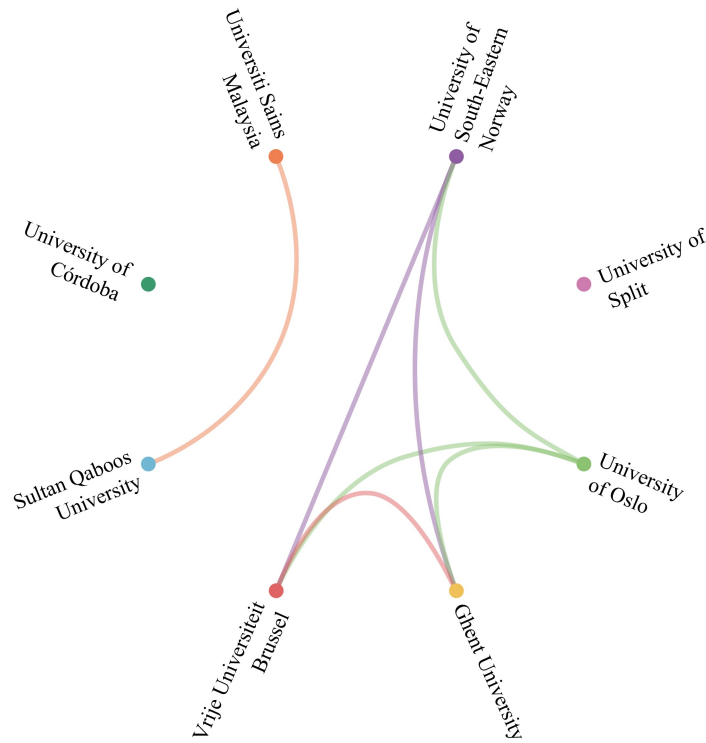
demonstrate the trend of data-driven decision-making expanding from localized optimization to full-cycle integration. Looking ahead, with deeper applications of GenAI and large educational models, teaching decisions will become more intelligent and humanized, though their implementation requires balancing technological innovation with ethical risks and building a synergistic ecosystem that harmonizes “data empowerment” with “education-centeredness”.

In terms of research output in this domain, the top 3 countries by number of core papers are Belgium, Norway, and Croatia; these same countries also rank highest in both total citations and average citations per paper (see Table 39). In terms of international collaboration, Norway and Belgium, the Sultanate of Oman and Malaysia have the most cooperation (see Figure 35). The leading institutions by number of papers are Ghent University, Vrije Universiteit Brussel, and University of Oslo; the same institutions also top the list by average citations per paper (see Table 40). With regard to institutional collaboration, Vrije Universiteit Brussel, University of South-Eastern Norway, University of Oslo, and Ghent University demonstrate the closest research partnership (see Figure 36). Citation data reveal the top 3 citing countries to be China, the USA, and Spain (see Table 41). The top citing institutions are University of Florida, Universiti

Sains Malaysia, and University of Tübingen (see Table 42). Figure 37 outlines the developmental roadmap for data driving intelligent decision-making across the entire teaching process.

**Figure 35** Collaboration network among major countries producing core papers on data driving intelligent decision-making across the entire teaching process.**Table 40** Major institutions producing core papers on data-driven intelligent decision-making across the entire teaching process

No.	Institution	Number of core papers	Percentage of core papers/%	Total citations	Average citations per paper	Mean publication year
1	Ghent University	1	25	760	760	2019.0
2	Vrije Universiteit Brussel	1	25	760	760	2019.0
3	University of Oslo	1	25	760	760	2019.0
4	University of South-Eastern Norway	1	25	760	760	2019.0
5	University of Split	1	25	427	427	2019.0
6	University of Córdoba	1	25	346	346	2020.0
7	Universiti Sains Malaysia	1	25	234	234	2019.0
8	Sultan Qaboos University	1	25	234	234	2019.0



**Figure 36** Collaboration network among major institutions producing core papers on data driving intelligent decision-making across the entire teaching process.

**Table 41** Major countries citing core papers on data driving intelligent decision-making across the entire teaching process

No.	Country	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	China	381	22.87	2022.5
2	USA	166	9.96	2022.2
3	Spain	116	6.96	2022.0
4	Germany	92	5.52	2022.5
5	Malaysia	90	5.40	2022.5
6	Saudi Arabia	83	4.98	2022.3
7	Australia	73	4.38	2022.1
8	UK	72	4.32	2022.5
9	India	71	4.26	2022.7
10	Indonesia	55	3.30	2022.6

**Table 42** Major institutions citing core papers on data driving intelligent decision-making across the entire teaching process

No.	Institution	Number of citing papers	Percentage of citing papers/%	Mean citing year
1	University of Florida	19	1.14	2022.8
2	Universiti Sains Malaysia	18	1.08	2022.6
3	University of Tübingen	15	0.90	2022.2
4	Taiwan Normal University	15	0.90	2022.3
5	Monash University	15	0.90	2022.6
6	King Abdulaziz University	15	0.90	2022.4
7	The University of Hong Kong	14	0.84	2021.9
8	University of Eastern Finland	14	0.84	2022.6
9	University of Oslo	13	0.78	2021.0
10	Central China Normal University	13	0.78	2022.7

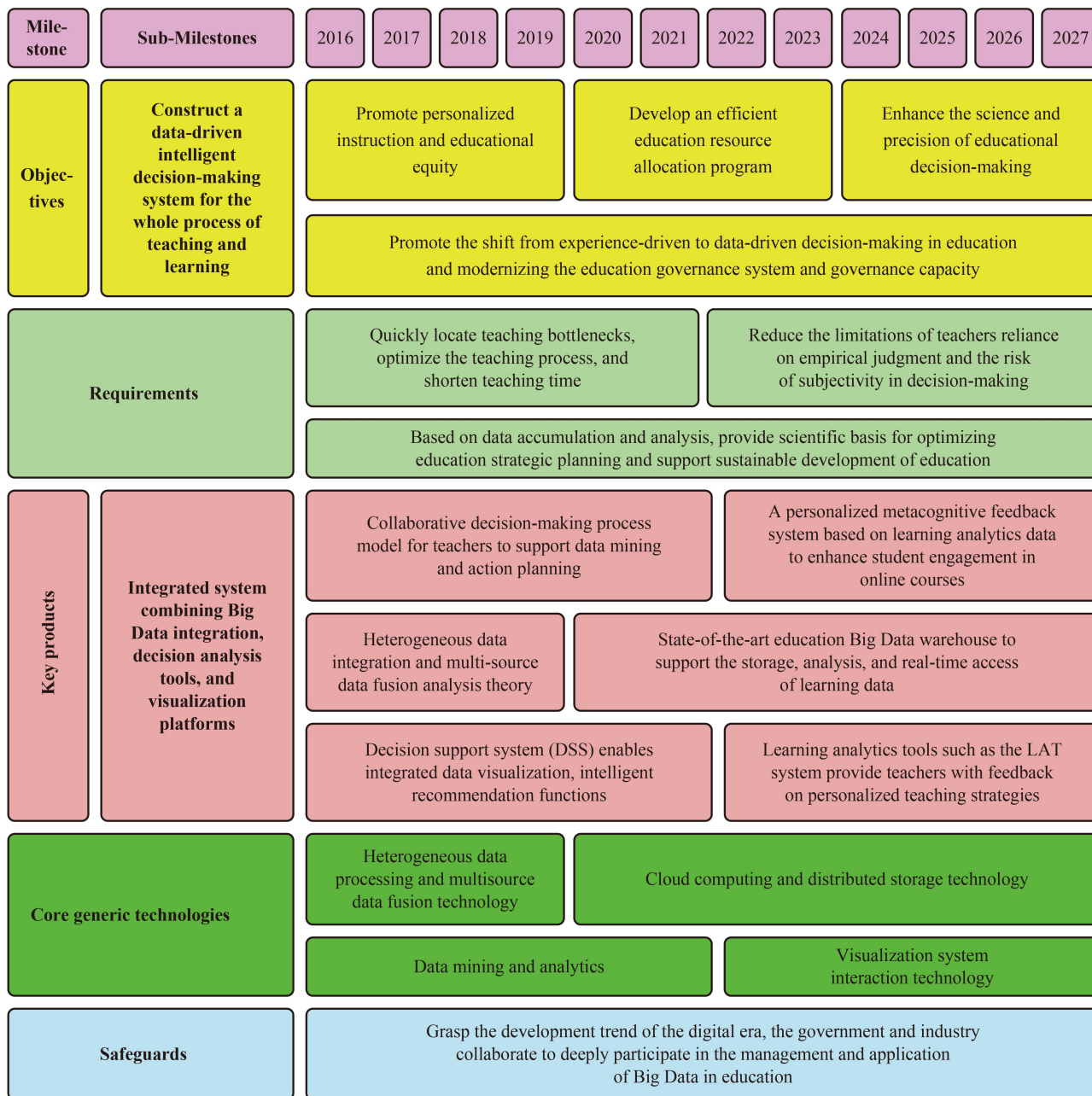


Figure 37 Developmental roadmap for data driving intelligent decision-making across the entire teaching process.

## Appendixes

### Appendix A Project Team Structure

#### 1. Guiding Organization

China Education Publishing & Media Group

#### 2. Publishing Organization

*Frontiers of Digital Education*

#### 3. Supporting Organizations

Wuhan University

Clarivate

#### 4. Project Team Members

##### (1) Advisory Committee

Yunsheng Feng, Chao Liu

##### (2) Working Group

###### Group Leaders

Fangzheng Tan, Zongkai Yang, Yongzhi Li

###### Chief Expert

Pingwen Zhang

###### Members (in alphabetical order by surname)

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Dan Wu, Di Wu, Fei Wu, Xiaofei Xu

##### (3) General Coordination Group

*Editorial Office of Frontiers of Digital Education*

Wenbo Jiang, Tingting Guo, Jin Wang, Runjie Li

###### Wuhan University

Dan Wu, Xin Jiang, Shaobo Liang, Chao Qiu,

Yingying Bao

###### Clarivate

Yiran Xu, Na Wang, Shihua Liu, Qingwen Yuan

##### (4) Data Support Group

###### Clarivate

Na Wang, Gunawan, Anastassia Obolenskaia

###### Wuhan University

Shaobo Liang, Siluo Yang, Ying Huang, Yong Huang, Chaocheng He

##### (5) Academic Interpretation

Dan Wu, Xin Jiang, Jun Deng, Chi Guo, Zhixiong Huang, Chenliang Li, Shaobo Liang, Bo Lyu, Liang Pei, Kun Qin, Chao Qiu, Fei Tang, Hao Wang, Sheng Wang, Ying Wang, Xiaohui Xiao, Bingxiang Yang, Feng Yu, Yiming Zhao, Yu Zhou

##### (6) English Translation Group

Jing Luo, Chengzhi Jiang, Min Huang

### Appendix B Terminological Clarification

This appendix delineates the analytical indicators employed in this report, along with their precise definitions (in alphabetical order).

#### Category normalized citation impact (CNCI):

A normalized bibliometric indicator derived by dividing a paper's citation count by the average citation count of all papers within the same subject category, publication year, and document type. For multidisciplinary papers, the CNCI represents the mean value across all relevant subject areas.

**Core papers:** Refers to highly cited papers positioned within the top 1% of citation frequency globally.

**ESI research fronts:** A proprietary classification within the Essential Science Indicators (ESI) framework. When a cluster of highly cited papers exhibits strong co-citation relationships and thematic coherence, it is algorithmically identified as a “research front”—an indicator of emergent and converging scholarly trajectories.

**Highly cited papers:** Designated by the ESI as papers ranking in the top 1% by citation frequency within their subject area and year of publication, based on a rolling ten-year citation window.

**High-impact papers:** Papers ranked within the top 10% of citation counts in their respective disciplines, calibrated by publication year and document type.

**Mean publication year:** The arithmetic mean of publication years for all core papers associated with a defined research hotspot.

**Number of citing papers:** The cumulative number of papers that have cited any of the identified core papers.

**Number of core papers:** The total number of core papers contributing substantively to a specific research hotspot.

**Number of papers:** Denotes the total count of scholarly outputs indexed in the Web of Science™ Core Collection—including SCIE, SSCI, and eight supplementary indices—between 2019 and 2024, restricted to the document types article, review, and proceedings paper.

**Paper percentage:** Represents the relative contribution of a country or institution to the corpus of core papers, expressed as a percentage of the global total. Within a particular hotspot, it denotes the share of core papers attributable to a given country or institution.

**Percentage of citing papers:** The share of citing papers originating from a specific country or institution, measured against the global total. Within a defined research hotspot, it reflects the percentage of citations received by core papers from a particular entity, relative to the total number of citing papers within that thematic area.

**Percentage of internationally collaborative papers:** The percentage of papers co-authored by contributors affiliated with institutions in different

countries, expressed as a percentage of the total dataset. This metric reflects the extent of cross-border academic engagement and international research integration.

**Publication year:** The year in which a scholarly work was formally published.

**Total citations:** The aggregate number of citations a paper has received from other documents indexed within the Web of Science™ Core Collection.

**Conflict of Interest** The authors declare that they have no conflicts of interest.

**Ethics Statements** The authors confirm that their Institutional Ethics Committee determined that no ethical review was required for this study. Written informed consent for participation was not required because all

participant data were anonymized prior to statistical analysis.

**Data Availability Statements** The authors confirm that all data generated or analyzed during this study are included in this published article.

**Authors Contributions** The details of the authors contributions were shown in Appendix A.

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