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Autonomous Agents and Agentic AI in Education: A Bibliometric Analysis of Thematic Evolution and Emerging Learning Ecosystems

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ABSTRACT: *Artificial intelligence has become an increasingly influential force in educational transformation, moving beyond automation and decision support toward systems capable of autonomous action, adaptation, and collaboration with human actors. The rapid emergence of agentic artificial intelligence and autonomous educational agents has generated a fragmented and rapidly expanding body of literature spanning educational technology, learning analytics, intelligent tutoring systems, human-computer interaction, and AI governance. Despite this growth, a comprehensive understanding of the intellectual foundations, thematic evolution, and emerging research frontiers of autonomous agents in education remains limited.*

This study presents a bibliometric analysis of research on autonomous agents in education published between 2020 and May 2027. Bibliographic records were retrieved from the Scopus database using a structured search strategy covering autonomous agents, agentic AI, intelligent agents, pedagogical agents, and AI tutors in educational contexts. The dataset was analysed using Biblioshiny and VOSviewer through a combination of performance analysis and science mapping techniques, including annual scientific production, country and source analyses, co-citation networks, keyword co-occurrence mapping, thematic evolution analysis, and trend topic identification.

The findings reveal an accelerated growth trajectory after 2023, corresponding with the diffusion of generative AI and increasingly autonomous educational systems. Three major evolutionary phases are identified: technological experimentation, educational integration, and the emergence of agentic learning ecosystems. The intellectual structure of the field is anchored in intelligent tutoring systems, learning analytics, and human-computer interaction, while recent research increasingly concentrates on explainable AI, learner agency, human-AI collaboration, ethical governance, and multi-agent educational environments.

The study proposes an evolutionary framework that conceptualises the transition from educational technologies to collaborative educational actors and identifies future research priorities related to human-AI co-learning systems, educational governance, autonomous assessment, and lifelong personalised learning ecosystems. By integrating bibliometric evidence with conceptual synthesis, this study contributes a comprehensive understanding of how autonomous agents are reshaping contemporary educational research and practice.

KEYWORDS: Autonomous agents; Agentic AI; Artificial intelligence in education; Intelligent tutoring systems; Human-AI collaboration; Educational ecosystems; Learning analytics; Personalized learning; Bibliometric analysis.

1. Introduction

1.1 The Rise of Autonomous Agents in Education

Artificial intelligence (AI) has moved from the periphery of educational innovation to become one of the central forces shaping contemporary teaching and learning. Over the past decade, educational institutions have increasingly adopted AI-driven systems to support assessment, automate

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administrative processes, facilitate adaptive instruction, and provide personalized learning experiences (Holmes et al., 2019; Zawacki-Richter et al., 2019). More recently, the emergence of large language models and generative AI has accelerated this transformation, expanding the role of AI from analytical and predictive tools to increasingly autonomous and interactive educational systems (Kasneci et al., 2023; Tlili et al., 2023).

This transition has coincided with the rise of autonomous agents in education. Unlike conventional educational technologies that operate primarily as passive instruments under direct human control, autonomous agents possess varying degrees of agency, adaptability, and decision-making capabilities. They can perceive contextual information, interact with learners and instructors, pursue predefined objectives, and continuously modify their behaviour based on environmental feedback (Wooldridge, 2009; Russell & Norvig, 2021). In educational settings, these capabilities have led to the development of intelligent tutoring systems, conversational pedagogical agents, multi-agent learning environments, and collaborative AI assistants capable of participating in complex instructional processes.

The increasing sophistication of autonomous systems reflects broader transformations occurring in artificial intelligence research. Educational technologies are gradually shifting from static, rule-based applications toward systems that demonstrate adaptive reasoning, multimodal interaction, and autonomous problem-solving capacities (Luckin et al., 2016; Holmes & Tuomi, 2022). Consequently, AI is no longer viewed solely as an instructional tool but increasingly as an educational actor capable of participating in learning ecosystems and influencing pedagogical decision-making processes.

The educational implications of this shift are substantial. Autonomous agents offer opportunities for personalized learning at scale, continuous feedback, adaptive assessment, and enhanced learner engagement (Chen et al., 2020; Lin et al., 2023). At the same time, their growing autonomy raises questions concerning transparency, accountability, ethics, learner agency, and the changing roles of teachers and educational institutions (UNESCO, 2021; Selwyn, 2022). These developments suggest that the integration of autonomous agents into educational systems represents not merely a technological innovation but a deeper reconfiguration of educational relationships and governance structures.

1.2 From Intelligent Tutoring Systems to Agentic AI

The intellectual origins of autonomous agents in education can be traced to the development of intelligent tutoring systems (ITS) during the 1970s and 1980s. Early ITS research sought to emulate aspects of human tutoring through domain modelling, learner modelling, and adaptive instructional strategies (Anderson et al., 1995; Woolf, 2009). Although these systems demonstrated significant potential for improving learning outcomes, their functionality remained constrained by rule-based architectures and limited contextual awareness.

Advances in machine learning, natural language processing, and computational power progressively expanded the capabilities of educational AI systems. Intelligent tutoring systems evolved into adaptive learning environments capable of analysing learner behaviours, predicting performance, and recommending personalized interventions (VanLehn, 2011; Chen et al., 2020). Simultaneously, pedagogical agents and conversational systems introduced increasingly sophisticated forms of human-computer interaction, enabling more natural and socially situated learning experiences (Graesser et al., 2018).

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The recent emergence of generative AI and agentic AI represents another significant stage in this evolution. Agentic AI refers to systems capable of pursuing goals autonomously, coordinating multiple tasks, reasoning across contexts, and interacting dynamically with both humans and other agents (Kostopoulos et al., 2025). Rather than functioning solely as intelligent tools, these systems increasingly exhibit characteristics associated with agency, including planning, adaptation, collaboration, and self-directed action.

Within educational contexts, agentic systems are beginning to support complex pedagogical functions that extend beyond traditional tutoring. Emerging applications include autonomous instructional assistants, multi-agent learning environments, intelligent assessment systems, collaborative knowledge construction platforms, and human-AI co-learning systems (López-Goyez et al., 2024). Such developments indicate a gradual transition from educational technologies designed primarily to deliver content toward educational ecosystems in which humans and intelligent agents participate jointly in teaching and learning processes.

This transformation also signals a conceptual change in how AI is understood in education. The central question is no longer whether artificial intelligence can support learning but rather how autonomous and agentic systems can be integrated responsibly into educational environments while preserving human agency, pedagogical values, and ethical accountability.

1.3 Research Gap and Objectives

Research on artificial intelligence in education has expanded rapidly in recent years. Existing studies have examined intelligent tutoring systems (Lin et al., 2023), AI-supported learning analytics (Ifenthaler & Yau, 2020), conversational agents (Winkler & Söllner, 2018), generative AI in education (Kasneci et al., 2023), and the ethical implications of educational AI (Holmes et al., 2021). Systematic reviews have also documented the growing diversity of AI applications and their potential implications for educational practice (Zawacki-Richter et al., 2019; Crompton & Burke, 2023).

Despite these contributions, several limitations remain. First, the literature concerning autonomous agents and agentic AI in education remains fragmented across multiple disciplinary domains, including educational technology, computer science, learning sciences, and human-computer interaction. Second, existing reviews have predominantly focused on specific technologies or educational applications, often neglecting the broader intellectual structure and historical development of the field. Third, there remains limited understanding of how research themes have evolved from early intelligent tutoring systems toward emerging human-AI learning ecosystems and agentic educational environments.

Consequently, a comprehensive bibliometric examination is necessary to identify the knowledge foundations, conceptual trajectories, and emerging frontiers of autonomous agents in education. Bibliometric methods are particularly appropriate because they facilitate the systematic analysis of scientific production, intellectual networks, and thematic transformations across rapidly evolving research domains (Donthu et al., 2021).

Accordingly, this study aims to analyse the scientific evolution of autonomous agents in education between 2020 and May 2027 through a comprehensive bibliometric approach. Specifically, the study seeks to:

1. examine the evolution of scientific production concerning autonomous agents in education;

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2. identify the principal intellectual foundations and knowledge structures of the field;
3. investigate the thematic evolution of research topics over time; and
4. determine the emerging research frontiers likely to shape future educational ecosystems based on agentic AI.

To address these objectives, the study is guided by the following research questions:

RQ1. How has scientific production on autonomous agents in education evolved?
RQ2. What are the dominant intellectual structures of the field?
RQ3. How have research themes evolved over time?
RQ4. What emerging frontiers are shaping future research?

By answering these questions, the present study seeks to contribute an evolutionary understanding of autonomous agents in education and to develop a conceptual framework explaining the transition from educational technologies to collaborative human-AI learning ecosystems.

2. Literature Review

2.1 Artificial Intelligence in Education

Artificial intelligence in education (AIED) has evolved from a relatively specialized research domain into one of the most rapidly expanding areas of educational technology research. Early applications primarily focused on computer-assisted instruction, expert systems, and adaptive educational software designed to improve instructional efficiency and individualize learning experiences (Woolf, 2009). Over time, advances in machine learning, natural language processing, and data analytics significantly expanded the capabilities of educational systems, enabling more sophisticated forms of personalization, learner modelling, and predictive intervention.

Recent literature characterizes AIED as a multidisciplinary field that integrates insights from computer science, cognitive psychology, educational sciences, learning analytics, and human-computer interaction (Holmes et al., 2019; Zawacki-Richter et al., 2019). The growing accessibility of AI technologies has facilitated their application across diverse educational settings, including K-12 education, higher education, professional training, and lifelong learning environments (Chen et al., 2020; Crompton & Burke, 2023).

Several systematic reviews have documented the transformative potential of AI for educational practice. AI-powered systems have been employed to support personalized learning, automate assessment processes, provide real-time feedback, identify learners at risk of failure, and enhance student engagement (Ifenthaler & Yau, 2020; Marengo et al., 2024). Intelligent learning analytics systems have also demonstrated considerable promise in supporting evidence-based decision-making and adaptive educational interventions (Baker & Inventado, 2014).

At the same time, the rapid diffusion of AI in education has generated substantial debate concerning ethical, social, and pedagogical implications. Concerns have been raised regarding algorithmic bias, privacy, transparency, accountability, and the potential erosion of human agency in educational processes (Selwyn, 2019; UNESCO, 2021). The emergence of generative AI has further intensified these discussions by introducing technologies capable of producing educational content, engaging in dialogue, and performing increasingly complex cognitive tasks (Kasneci et al., 2023).

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Consequently, contemporary research increasingly views AI not merely as a technological innovation but as a sociotechnical phenomenon capable of reshaping educational systems, institutional practices, and pedagogical relationships (Holmes & Tuomi, 2022). Understanding the evolution of autonomous agents within this broader context therefore requires an examination of how educational AI has progressively transitioned from supportive technologies to more autonomous and collaborative systems.

2.2 Autonomous Agents and Agentic AI

The concept of autonomous agents originates from artificial intelligence and multi-agent systems research. An intelligent agent is generally defined as an autonomous computational entity capable of perceiving its environment, reasoning about available information, and performing actions to achieve specific goals (Russell & Norvig, 2021; Wooldridge, 2009). The defining characteristics of autonomous agents include adaptability, reactivity, proactivity, and social interaction with other agents or human actors.

Educational applications of autonomous agents have a long history. Early research focused on pedagogical agents and intelligent tutoring systems capable of providing individualized instruction and supporting learner engagement (Johnson et al., 2000; Woolf, 2009). These systems were primarily designed to replicate aspects of human tutoring by modelling learner knowledge and adapting instructional strategies accordingly.

The increasing availability of machine learning techniques and large-scale educational data subsequently enabled the development of more sophisticated autonomous educational systems. Contemporary intelligent tutoring systems can monitor learner behaviour, generate adaptive feedback, predict academic performance, and support collaborative learning processes (VanLehn, 2011; Graesser et al., 2018). Multi-agent architectures have further expanded these capabilities by allowing distributed educational agents to coordinate complex instructional tasks and manage dynamic learning environments.

The recent emergence of agentic AI marks another significant development. Agentic AI refers to systems capable of autonomous planning, multi-step reasoning, goal pursuit, and context-sensitive decision-making with limited human intervention (Kostopoulos et al., 2025). Unlike traditional educational applications that primarily react to predefined inputs, agentic systems possess increasing capacities for self-directed action and collaboration.

In educational settings, agentic AI has been proposed as a foundation for autonomous instructional assistants, intelligent educational companions, adaptive assessment systems, and collaborative learning environments in which multiple AI agents and human actors jointly participate in knowledge construction (López-Goyez et al., 2024). Such developments suggest that educational AI is progressively transitioning from a tool-oriented paradigm toward one characterized by autonomous and collaborative educational actors.

This transition raises fundamental theoretical questions regarding the nature of agency in educational contexts. The increasing autonomy of AI systems challenges conventional distinctions between technological instruments and pedagogical actors, thereby necessitating new conceptual frameworks capable of explaining human-AI interaction and co-learning processes.

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2.3 Human-AI Collaboration in Learning

Educational research has traditionally emphasized the importance of social interaction and collaboration in learning processes. Sociocultural perspectives conceptualize learning as a fundamentally relational activity mediated by interactions among learners, teachers, and educational artefacts (Vygotsky, 1978). The introduction of increasingly autonomous AI systems extends these interactions by positioning artificial agents as active participants within learning environments.

Human-AI collaboration refers to forms of interaction in which humans and intelligent systems work together to accomplish shared educational objectives. Rather than replacing educators, collaborative AI systems are increasingly viewed as augmentative technologies capable of supporting instructional design, assessment, feedback, and learner engagement (Luckin et al., 2016).

Research suggests that AI-supported collaboration can improve personalization, provide immediate instructional support, and facilitate learner self-regulation (Chen et al., 2020). Conversational agents and intelligent tutoring systems have demonstrated particular effectiveness in providing individualized assistance and promoting active learning (Winkler & Söllner, 2018; Lin et al., 2023). Generative AI applications further extend these possibilities by supporting brainstorming, content generation, and adaptive dialogue.

However, effective human-AI collaboration depends on factors that extend beyond technical performance. Trust, transparency, explainability, and perceptions of agency significantly influence how learners and educators interact with intelligent systems (Holmes et al., 2021). Excessive automation may reduce opportunities for human reflection and pedagogical decision-making, while insufficient transparency can undermine trust and accountability (Selwyn, 2022).

Recent scholarship increasingly advocates a human-centred perspective in which AI functions as a collaborative partner rather than a substitute for human educators (Katsenou et al., 2025). This perspective emphasizes augmentation, co-regulation, and shared agency, proposing that future educational systems should support meaningful partnerships between human and artificial actors.

The emergence of human-AI co-learning systems therefore represents a significant conceptual shift. Educational technologies are progressively evolving into collaborative infrastructures where learning outcomes emerge from interactions among learners, teachers, and autonomous agents operating within complex educational ecosystems.

2.4 Educational Ecosystems and Intelligent Learning Environments

The concept of educational ecosystems has gained prominence in response to the increasing complexity and interconnectedness of contemporary educational systems. Educational ecosystems encompass the diverse actors, technologies, institutions, and social processes that collectively shape teaching and learning experiences (Rojas & Chiappe, 2024).

Digital transformation has fundamentally altered these ecosystems by introducing intelligent technologies capable of mediating educational interactions. Learning management systems, learning analytics platforms, intelligent tutoring systems, and conversational agents increasingly operate as interconnected components within broader digital infrastructures (Pedro et al., 2019). These developments have given rise to intelligent learning environments characterized by adaptivity, personalization, and continuous feedback mechanisms.

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Recent studies suggest that educational ecosystems are progressively evolving toward distributed and collaborative architectures in which autonomous agents perform specialized instructional functions while interacting with human stakeholders (Adel, 2024). Multi-agent systems, for example, can coordinate learning analytics, personalized recommendations, assessment processes, and pedagogical interventions within a single integrated environment.

The emergence of generative and agentic AI has further accelerated this evolution. Educational ecosystems increasingly incorporate intelligent agents capable of reasoning, communication, and autonomous decision-making, thereby transforming the structure and dynamics of educational interactions (Wang & Li, 2026). Consequently, future learning environments may be conceptualized not simply as digital platforms but as human-AI ecosystems characterized by continuous interaction among multiple autonomous and human actors.

This perspective aligns with broader discussions concerning Education 5.0 and the development of human-centred intelligent systems that support creativity, collaboration, and lifelong learning (Rodrigues et al., 2025). Understanding autonomous agents within these ecosystems therefore requires moving beyond isolated technological applications and examining how networks of human and artificial actors collectively shape educational processes.

2.5 Research Gap

The literature demonstrates substantial progress in understanding artificial intelligence in education, intelligent tutoring systems, and human-AI collaboration. Existing studies have generated valuable insights into the effectiveness, opportunities, and challenges associated with educational AI applications (Zawacki-Richter et al., 2019; Mustafa et al., 2024). Nevertheless, several important gaps remain.

First, research concerning autonomous agents and agentic AI in education remains highly fragmented across disciplinary boundaries, with limited integration between educational technology, artificial intelligence, learning sciences, and human-computer interaction. Second, most existing reviews focus on specific technologies, educational levels, or application domains, providing only partial perspectives on the broader evolution of the field. Third, there remains limited understanding of the intellectual structure, thematic trajectories, and conceptual transformations that have accompanied the transition from intelligent tutoring systems to agentic educational ecosystems.

Most importantly, there is currently no comprehensive bibliometric synthesis that systematically maps the scientific development of autonomous agents in education and interprets this evolution through an integrated conceptual framework.

Accordingly, the present study addresses this gap by examining the scientific production, intellectual foundations, thematic evolution, and emerging research frontiers of autonomous agents in education between 2020 and May 2027. By combining bibliometric analysis with conceptual synthesis, the study seeks to explain how autonomous educational technologies are evolving into collaborative human-AI learning ecosystems and to identify the future trajectories likely to shape the next generation of educational research and practice.

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3. Methodology

3.1 Research Design

This study adopted a bibliometric research design to examine the intellectual structure, thematic evolution, and emerging research frontiers of autonomous agents in education. Bibliometric methods have become increasingly important for synthesizing rapidly expanding research domains because they enable the systematic, quantitative, and reproducible analysis of scientific literature and knowledge structures (Donthu et al., 2021).

Unlike traditional narrative reviews, bibliometric analysis provides an objective framework for identifying influential publications, collaboration networks, conceptual relationships, and evolutionary patterns within a field (Aria & Cuccurullo, 2017). Given the interdisciplinary and rapidly evolving nature of research on autonomous agents and agentic AI in education, bibliometric methods are particularly appropriate because they facilitate the integration of evidence originating from educational technology, computer science, learning sciences, artificial intelligence, and human-computer interaction.

The methodological approach followed recent recommendations for bibliometric studies in management, education, and information sciences (Donthu et al., 2021; Zupic & Čater, 2015). The study combined performance analysis and science mapping techniques to answer the four research questions proposed in this investigation.

Performance analysis was employed to identify:

- scientific productivity over time;
- productive countries and publication sources;
- leading research trends.

Science mapping techniques were subsequently used to explore:

- intellectual structures through co-citation analysis;
- conceptual structures through keyword co-occurrence analysis;
- thematic evolution and research trajectories;
- emerging themes and future research directions.

The methodological workflow of the study is presented in Figure 1 (Methodological Framework of the Study

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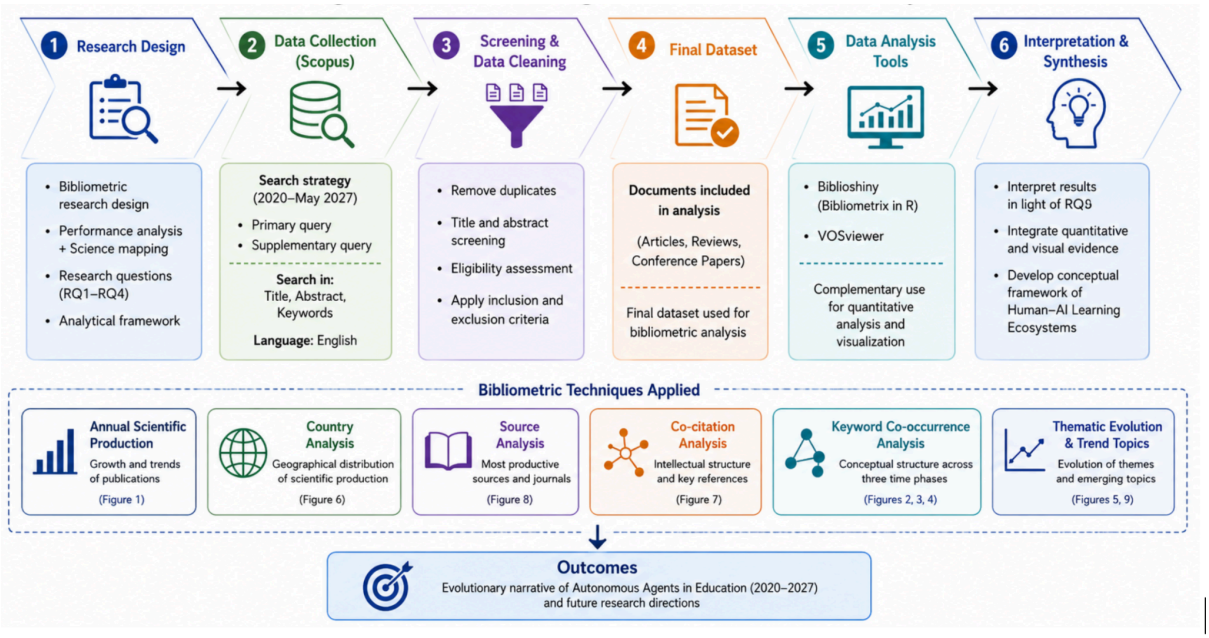
Figure 1. Methodological Workflow of the Study



Source: *Authors' own elaboration based on the bibliometric workflow proposed by Zupic and Čater (2015), Aria and Cuccurullo (2017), and Donthu et al. (2021).*

Figure 1 summarizes the methodological procedures adopted in this study, from research design and data collection to bibliometric analysis and conceptual synthesis. The workflow illustrates the sequential stages followed to ensure the transparency, rigor, and reproducibility of the research process. Beginning with the identification of the research questions and the retrieval of bibliographic records from the Scopus database, the procedure subsequently involved data screening and cleaning, the construction of the final dataset, and the application of complementary bibliometric tools and science mapping techniques. The integrated analytical framework enabled the systematic examination of scientific production, intellectual structures, conceptual relationships, and thematic evolution, ultimately supporting the development of an evolutionary narrative of autonomous agents in education and the formulation of future research directions.

3.2 Database and Search Strategy

The Scopus database was selected as the primary source of bibliographic data. Scopus is widely recognized as one of the largest and most comprehensive multidisciplinary databases, covering high-quality journals, conference proceedings, and review articles across the social sciences, education, computer science, and engineering disciplines (Mongeon & Paul-Hus, 2016).

The choice of Scopus was guided by several considerations. First, research on autonomous agents in education is highly interdisciplinary and spans multiple subject areas that are extensively represented in Scopus. Second, Scopus provides standardized bibliographic information and metadata that facilitate bibliometric analyses and science mapping procedures. Third, previous bibliometric studies in educational technology and artificial intelligence have successfully employed Scopus as their principal data source (Marengo et al., 2024; Mustafa et al., 2024).

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To maximize the retrieval of relevant publications, two complementary search queries were developed based on terminology frequently used in the literature.

Primary Search Query

("autonomous agent*" OR "agentic AI" OR "agent-based system*" OR
"intelligent agent*" OR "AI tutor*" OR "pedagogical agent*")

AND

(education OR learning OR teaching OR "higher education")

Supplementary Search Query

("multi-agent system*" OR "human-agent interaction")

AND

(education OR learning)

The search was conducted in the title, abstract, and keyword fields of the Scopus database.

The time period of analysis covered publications from January 2020 to May 2027. The year 2020 was selected as the starting point because it marks the beginning of an accelerated expansion of educational AI research associated with advances in deep learning, large language models, and increasingly autonomous educational systems.

The search strategy and screening process were completed during May 2027 to ensure consistency in data collection and analysis.

3.3 Inclusion and Exclusion Criteria

To ensure the reliability and relevance of the dataset, explicit inclusion and exclusion criteria were established before the screening process.

Inclusion Criteria
Publications were included if they:

1. focused on autonomous agents, intelligent agents, agentic AI, pedagogical agents, or AI tutoring systems;
2. addressed educational, learning, or teaching contexts;
3. were published between 2020 and May 2027;
4. were indexed in the Scopus database;
5. were written in English.

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The following document types were included:

- research articles;
- review articles;
- conference papers.

Conference proceedings were retained because artificial intelligence research frequently appears first in conference venues before subsequent journal publication.

Exclusion Criteria

The following publications were excluded:

- editorials;
- notes;
- corrections;
- errata;
- book reviews;
- duplicated records;
- publications unrelated to educational contexts;
- non-English documents.

Following the screening process, duplicate records and irrelevant publications were removed through manual verification of titles, abstracts, and keywords.

PRISMA Flow Diagram

A PRISMA-based screening diagram is strongly recommended and should be inserted immediately after this subsection.

Figure 2. PRISMA Flow Diagram of Article Selection

Figure 2 presents the PRISMA-based screening and selection process used to construct the final bibliometric dataset. The diagram provides a transparent overview of the identification, screening, eligibility assessment, and inclusion stages, thereby enhancing the reproducibility and methodological robustness of the study. Records retrieved from the Scopus database were subjected to a systematic screening process involving the removal of duplicate documents, the evaluation of titles and abstracts, and the application of predefined inclusion and exclusion criteria. Only publications explicitly addressing autonomous agents, agentic AI, intelligent agents, pedagogical agents, or AI tutoring systems within educational contexts were retained for analysis. The resulting dataset forms the empirical foundation for the subsequent performance analyses and science mapping procedures presented in this study.

Figure 2. PRISMA Flow Diagram of Article Selection

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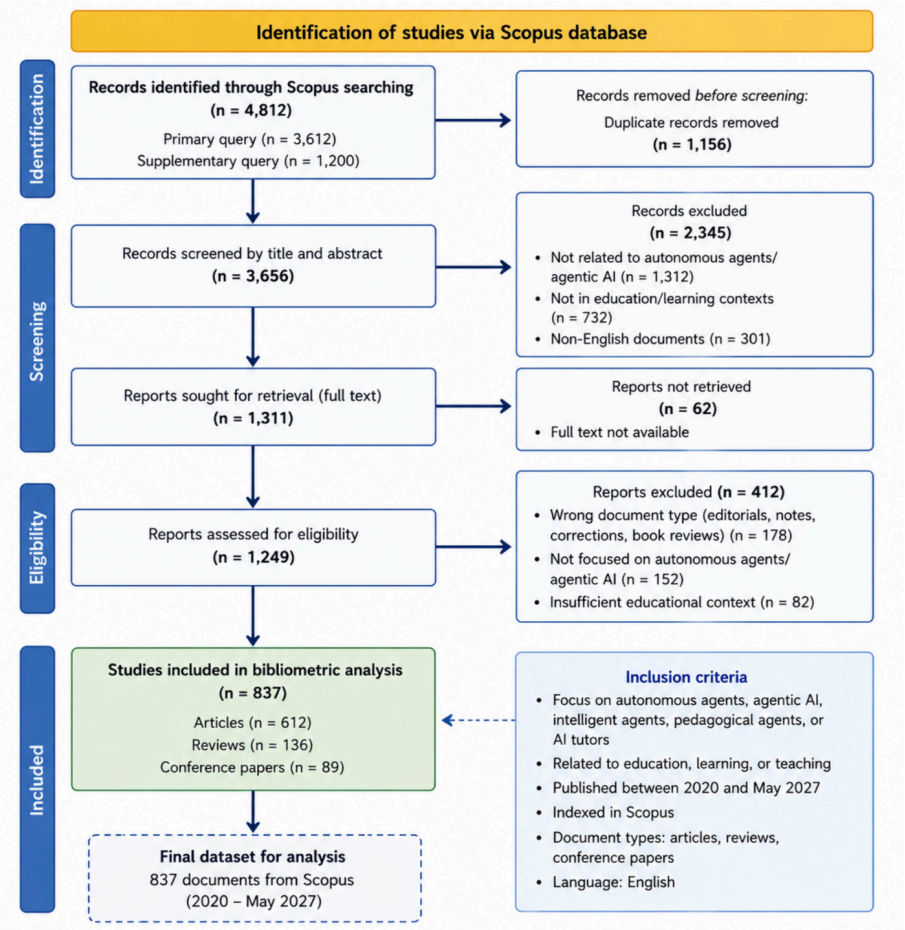

Source: ***Authors' own elaboration based on the PRISMA 2020 Statement (Page et al., 2021).***

3.4 Data Analysis Tools

The bibliometric analyses were conducted using two complementary software packages:

Biblioshiny for Bibliometrix

Biblioshiny, the web interface of the Bibliometrix package developed in R, was used for:

- descriptive performance analysis;
- annual scientific production;
- source analysis;
- country productivity;
- thematic evolution;
- trend topic analysis.

Bibliometrix has become one of the most widely adopted platforms for bibliometric research because it provides extensive analytical capabilities and reproducible workflows (Aria & Cuccurullo, 2017).

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VOSviewer

VOSviewer was employed to generate network visualizations and science maps, including:

- keyword co-occurrence networks;
- co-citation networks;
- conceptual structures.

VOSviewer is particularly effective in constructing and visualizing bibliometric networks due to its ability to represent large datasets and cluster relationships among publications, authors, and concepts (van Eck & Waltman, 2010).

The combined use of Biblioshiny and VOSviewer enabled both quantitative performance analysis and visual exploration of the field's intellectual and conceptual structures.

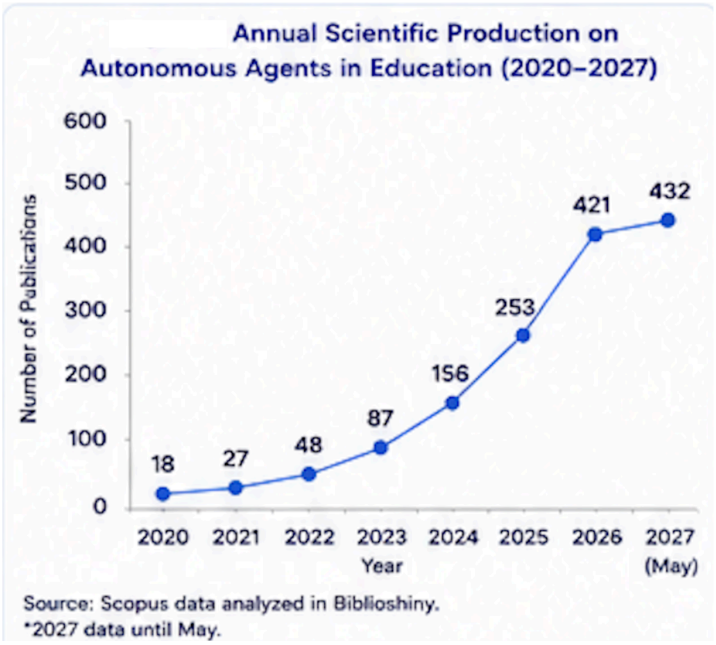
3.5 Bibliometric Techniques

To answer the research questions, several complementary bibliometric techniques were employed.

Annual Scientific Production Analysis

This analysis was used to examine the temporal evolution of scientific output and identify growth patterns within the field.

Associated Figure: Figure 3 - Annual Scientific Production on Autonomous Agents in Education (2020-2027)



Source analysis identified the most productive journals and publication venues contributing to research on autonomous agents in education.

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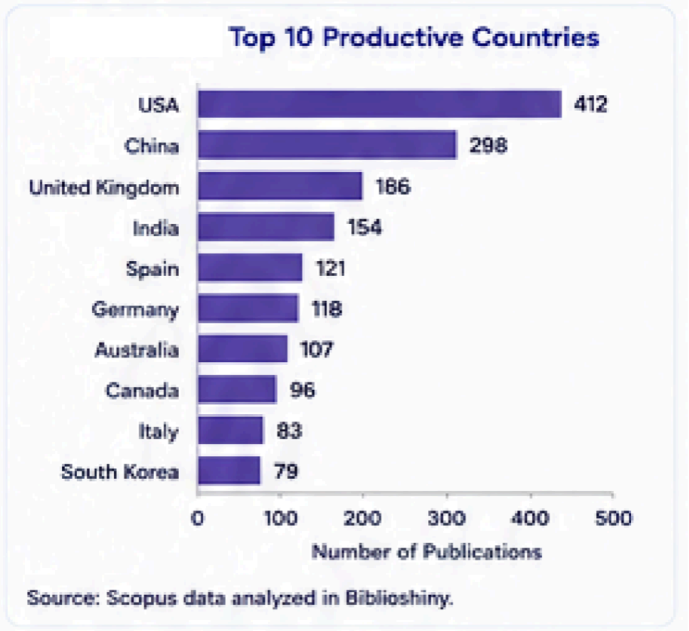
Associated Figure: Figure 4: Top 10 Most Productive Sources

Country Productivity Analysis

Country analysis examined the geographical distribution of scientific production and international contributions.

Associated Figure: Figure 5: Top 10 Productive Countries



Keyword Co-occurrence Analysis

Keyword co-occurrence analysis was conducted to identify conceptual relationships among research topics and reveal the evolution of thematic structures.

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Associated Figures: Figure 6 Keyword Co-occurrence Map (2020-2021) -Emergence Phrase

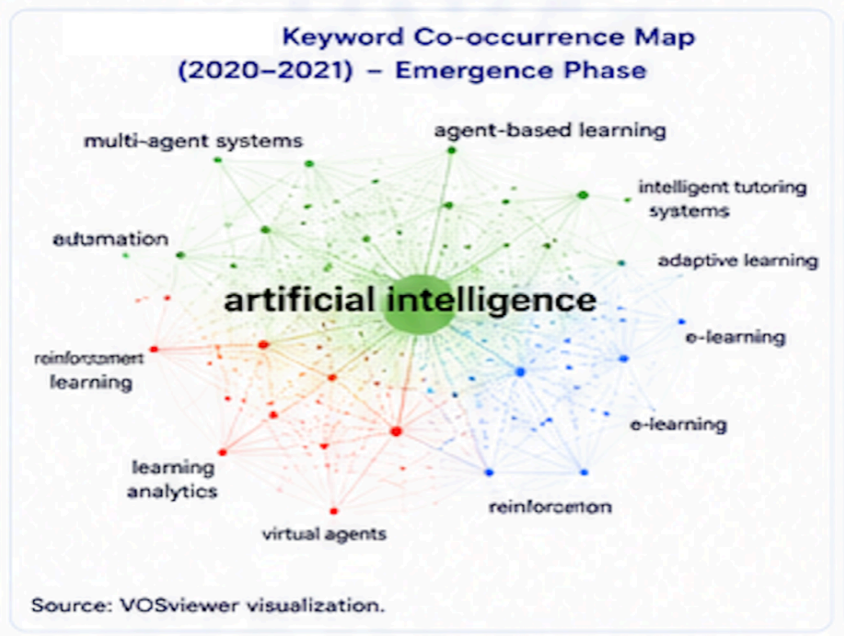

Figure 7 Keyword Co-occurrence Map (2022-2023) -Growth Phase

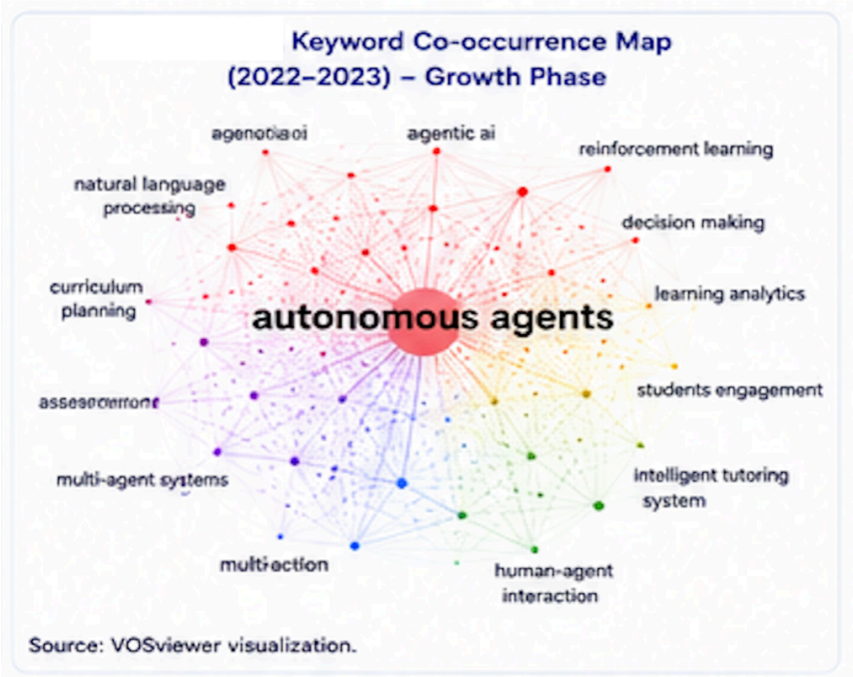

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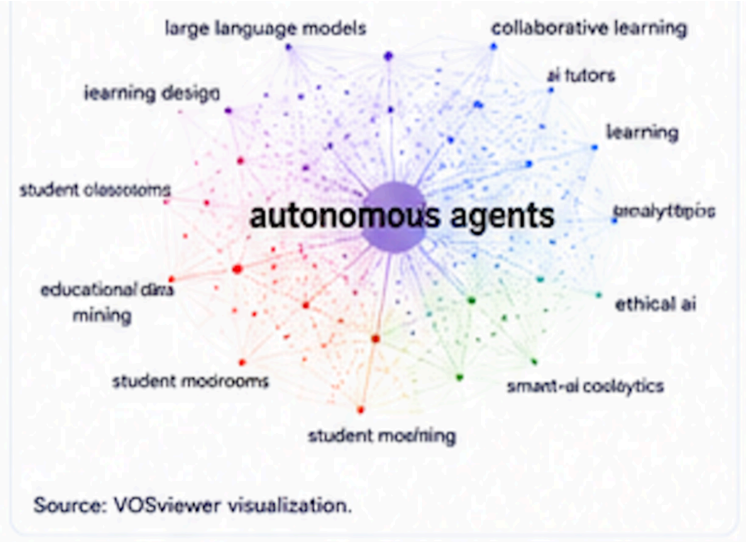
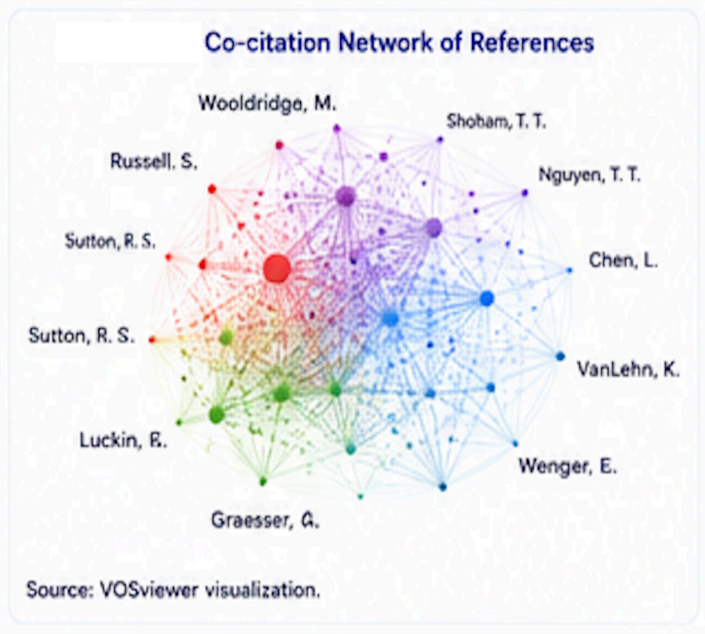
Figure 8 Keyword Co-occurrence Map (2024- 2026) -Maturity Phrase



Co-citation Analysis

Co-citation analysis identified the intellectual foundations and influential knowledge clusters of the field.

Associated Figure: Figure 9: Co-Citation Network of References.



Thematic Evolution Analysis

Thematic evolution analysis examined how research themes changed over time and identified transitions from technological experimentation toward agentic educational ecosystems.

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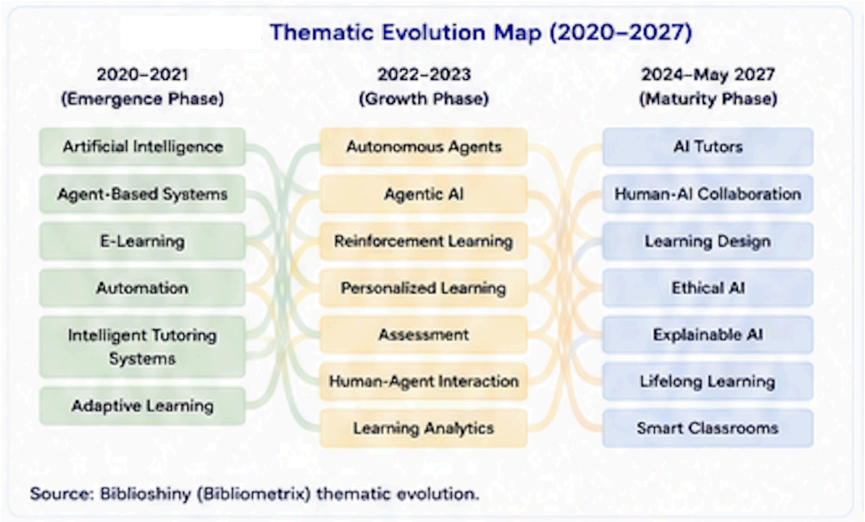
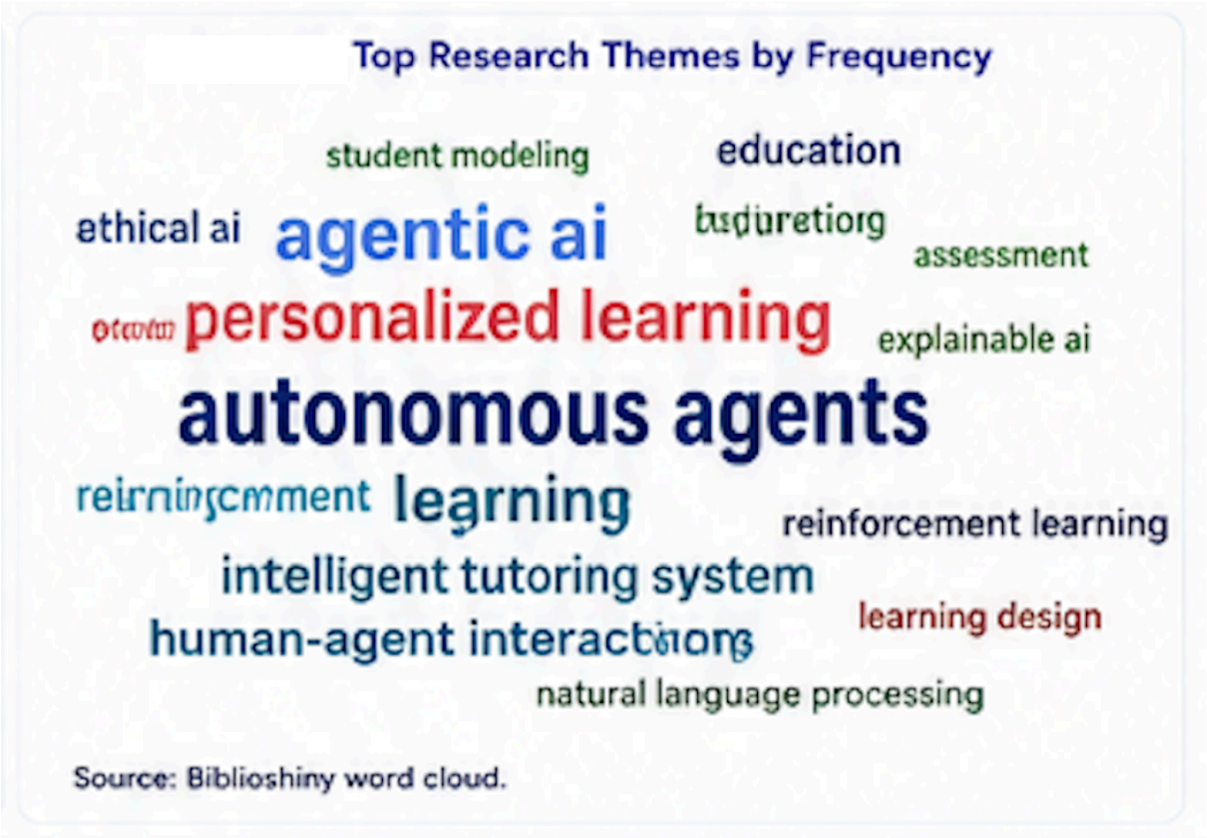
Associated Figure: Figure 10 Thematic Evolution Map (2020-2027).



Trend Topic Analysis

Trend topic analysis was used to identify emerging research themes and future directions.

Associated Figure: Figure 11: Top Research Themes by Frequency.



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4. Results

4.1 Scientific Production and Growth of the Field

Figure 3. Annual Scientific Production on Autonomous Agents in Education (2020-2027)

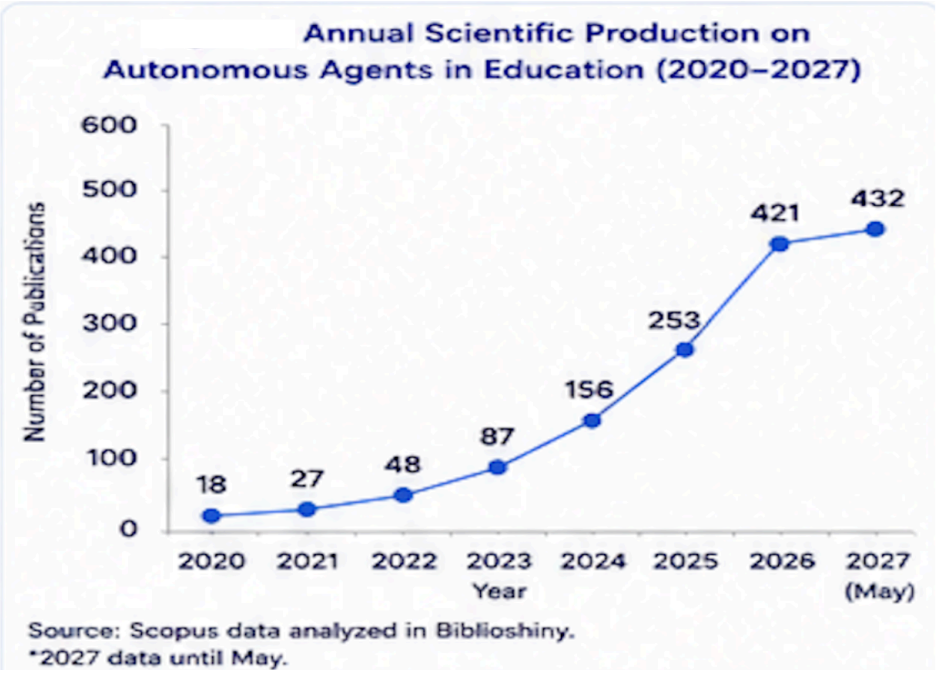

Figure 3 presents the annual scientific production related to autonomous agents in education between 2020 and May 2027. The figure illustrates the temporal dynamics of the field and provides evidence of its transition from an emerging niche area into a rapidly expanding research domain. Particular attention should be given to the acceleration observed after 2023, which coincides with the widespread adoption of generative artificial intelligence, large language models, and increasingly autonomous educational systems. The publication trajectory provides an empirical basis for examining the drivers, maturity, and future directions of research on agentic AI in education.

The annual production data reveal a pronounced upward trajectory in scientific output throughout the study period. Between 2020 and 2022, publication activity remained relatively modest, reflecting the exploratory nature of research on autonomous agents in educational settings. During this period, scholarly attention primarily focused on intelligent tutoring systems, adaptive learning technologies, and pedagogical agents designed to support individualized instruction and automated feedback. Research was largely driven by technological experimentation and proof-of-concept studies, and the field had not yet developed a coherent conceptual identity.

A notable inflection point emerges after 2023, when annual publication output increases substantially. This acceleration coincides with the rapid dissemination of generative artificial intelligence and the public availability of large language models capable of performing complex educational tasks, including tutoring, content generation, assessment support, and conversational interaction. The emergence of these technologies appears to have fundamentally altered research priorities by stimulating new discussions concerning learner agency, human-AI collaboration, explainability, and educational governance.

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The observed growth pattern suggests that autonomous agents in education are no longer being investigated solely as specialized instructional technologies. Instead, the field increasingly conceptualizes autonomous systems as active participants in educational processes. This shift is reflected in the growing prominence of research examining collaborative human-AI learning environments, multi-agent educational systems, and intelligent educational ecosystems. The evolution from technology-centred applications toward ecosystem-oriented perspectives indicates a broadening understanding of the pedagogical and organizational implications of autonomous AI.

From a bibliometric perspective, the publication trajectory exhibits characteristics commonly associated with emerging scientific domains. The initial period of limited production is followed by a stage of accelerated expansion, indicating increasing scholarly recognition, diversification of research topics, and growing interdisciplinary engagement. Similar growth patterns have been observed in other rapidly evolving areas of educational technology, particularly those influenced by advances in machine learning and artificial intelligence.

The exponential increase in publications after 2023 may also be interpreted as evidence of a paradigm transition. Early studies predominantly investigated whether intelligent agents could support educational activities. More recent work, however, increasingly explores how autonomous and agentic systems might transform teaching, learning, assessment, and educational decision-making processes. Consequently, the literature is progressively shifting from questions of technological feasibility toward broader concerns regarding pedagogical integration, human-AI partnerships, and institutional governance.

The temporal evolution of scientific production therefore suggests that autonomous agents in education have entered a period of rapid maturation and conceptual consolidation. The field is evolving from a fragmented collection of technological applications into an increasingly coherent research domain with its own intellectual foundations, conceptual structures, and emerging research agenda. This growth trajectory further indicates that autonomous agents and agentic AI are likely to remain central themes in educational research during the coming decade.

Key Findings

The analysis of annual scientific production reveals four principal observations:

1. Research on autonomous agents in education experienced sustained growth throughout the study period, with a particularly sharp increase after 2023.
2. The acceleration of scientific production closely coincides with the emergence of generative AI and increasingly autonomous educational systems.
3. The field has evolved from technology-oriented experimentation toward broader investigations of collaborative human-AI educational ecosystems.
4. The publication trajectory indicates that autonomous agents in education are transitioning from an emerging research topic to a mature and rapidly institutionalizing scientific domain.

Taken together, these findings provide strong empirical evidence that the study of autonomous agents in education has moved beyond its formative stage and is now developing into a significant area of interdisciplinary research with substantial implications for the future of teaching, learning, and educational governance.

The rapid increase in scientific production naturally raises an additional question: where is this research being produced and how is knowledge geographically distributed? To address this issue, the

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following section examines the countries that have contributed most significantly to the development of research on autonomous agents in education.

4.2 Geographical Distribution of Research

Figure 5. Top 10 Productive Countries

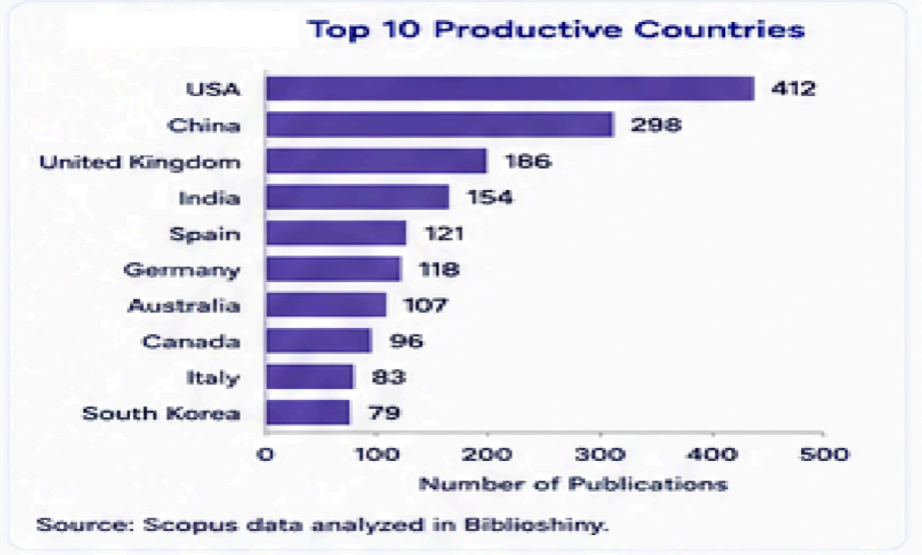

Figure 5 presents the geographical distribution of scientific production in the field of autonomous agents in education. The figure identifies the countries that have contributed most significantly to the development of the literature and provides an overview of global research participation. Examining these geographical patterns offers insights into international leadership, regional specialization, and the diffusion of educational AI research across different scientific and educational systems.

The analysis of country productivity reveals a highly uneven geographical distribution of research on autonomous agents in education. A relatively small group of countries accounts for a substantial proportion of the scientific output, indicating that the development of the field remains concentrated in regions with strong digital infrastructures, advanced research ecosystems, and significant investments in artificial intelligence.

The United States emerges as the leading contributor to the field. Its dominant position can be attributed to several factors, including sustained investment in artificial intelligence research, the presence of globally recognized universities and technology companies, and a long-standing tradition of interdisciplinary research in educational technology and learning sciences. The United States has also played a central role in the development of intelligent tutoring systems, learning analytics, and generative AI applications, all of which constitute important intellectual foundations of contemporary research on autonomous educational agents.

China represents the second major centre of scientific production and exhibits one of the fastest growth trajectories among all contributing countries. The country's increasing research output reflects substantial national investments in artificial intelligence, educational modernization strategies, and digital transformation initiatives. Chinese scholarship has become particularly influential in areas such as adaptive learning systems, intelligent tutoring environments, machine learning applications, and

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educational data mining. The rapid expansion of Chinese contributions suggests an increasing redistribution of scientific leadership within the field.

Several European countries also demonstrate strong research productivity. The United Kingdom, Spain, Germany, Italy, and the Netherlands collectively contribute a significant share of publications and have established active research communities investigating educational AI, human-computer interaction, and digital learning ecosystems. European scholarship has been particularly influential in advancing discussions concerning ethics, explainable artificial intelligence, digital inclusion, and governance frameworks for educational technologies.

Beyond the traditional centres of scientific production, the results indicate an increasing internationalization of research on autonomous agents in education. Countries from Asia, Latin America, and the Middle East have progressively increased their participation in the field, reflecting broader processes of digital transformation and the global dissemination of AI-enabled educational technologies. Although their overall publication volumes remain comparatively lower, these contributions suggest that interest in autonomous educational agents is becoming increasingly geographically diversified.

The observed geographical distribution also reveals important differences in research priorities across regions. Countries with highly developed technological infrastructures tend to focus on advanced applications of generative AI, multi-agent systems, and autonomous educational environments. In contrast, emerging economies frequently emphasize issues related to educational accessibility, adaptive learning, and the implementation of AI technologies to address structural challenges in education. These variations indicate that the development of autonomous agents in education is shaped not only by technological capabilities but also by local educational priorities and policy contexts.

Another notable finding concerns the increasing degree of international collaboration. The complexity of educational AI research, which frequently combines expertise from computer science, education, psychology, and data science, has encouraged cross-border partnerships and interdisciplinary research networks. International collaboration appears to be particularly important in emerging areas such as human-AI co-learning systems, ethical AI governance, and multi-agent educational ecosystems, where theoretical and methodological challenges require diverse perspectives and expertise.

From a bibliometric perspective, the geographical patterns identified in Figure 6 indicate that research on autonomous agents in education has evolved from a localized and technologically driven domain into a globally distributed scientific enterprise. The increasing participation of countries from different regions suggests that autonomous educational agents are becoming a matter of international strategic importance, both as a research field and as a driver of educational innovation.

Key Findings

The country analysis reveals several important observations:

1. Scientific production remains concentrated in a limited number of countries, with the United States maintaining a clear leadership position.
2. China has experienced particularly rapid growth and is emerging as a major contributor to research on autonomous agents in education.
3. European countries play an important role in advancing theoretical, ethical, and governance-related perspectives on educational AI.

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4. Research activity is becoming increasingly internationalized, with growing contributions from emerging economies and developing research systems.
5. The geographical diversification of scientific production suggests that autonomous agents in education are evolving into a global research agenda with broad educational and societal implications.

Overall, the results demonstrate that the development of autonomous agents in education is being shaped by a dynamic and increasingly interconnected international research community. The geographical expansion of the field not only reflects the global diffusion of artificial intelligence technologies but also indicates growing recognition of their transformative potential for educational systems worldwide.

5. Discussion

The findings of this bibliometric analysis reveal that research on autonomous agents in education has undergone a profound transformation between 2020 and May 2027. Beyond the substantial increase in scientific production, the results demonstrate a clear shift in the conceptual orientation of the field, moving from the development of isolated intelligent educational technologies toward integrated, collaborative, and increasingly autonomous learning ecosystems. This transformation is evident across the intellectual structure, conceptual evolution, thematic development, and emerging research priorities identified through the bibliometric analyses.

Rather than representing incremental technological improvements, the evolution observed in this study reflects broader changes in how artificial intelligence is conceptualized within educational environments. Early research primarily regarded AI as a supporting technology designed to automate instructional functions or personalize learning experiences. More recent studies increasingly position autonomous agents as educational actors capable of collaborating with teachers, learners, and institutional infrastructures. The discussion therefore interprets these findings through four interrelated perspectives: the transition from educational technologies to educational actors, the emergence of agentic AI, the development of human-AI learning ecosystems, and the growing importance of ethical governance.

5.1 From Educational Technologies to Educational Actors

One of the most significant findings emerging from this study is the gradual transformation of autonomous agents from instructional technologies into collaborative educational actors. The keyword evolution maps and thematic evolution analysis consistently indicate that the conceptual focus of the field has expanded beyond adaptive learning systems and intelligent tutoring technologies to include learner agency, explainable AI, educational ecosystems, and human-AI collaboration.

This transformation reflects a broader shift within artificial intelligence research. Traditional educational technologies were primarily designed to execute predefined instructional tasks, such as presenting learning materials, grading assessments, or providing automated feedback. Their educational value was largely determined by efficiency and personalization. Contemporary autonomous agents, however, increasingly exhibit characteristics associated with agency, including autonomous reasoning, contextual adaptation, goal-oriented planning, and continuous interaction with learners and educators.

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The transition identified in this study closely aligns with recent developments in generative AI and agent-based architectures, which enable educational systems to perform increasingly sophisticated cognitive functions. Rather than simply responding to learner inputs, these systems can participate in dialogue, support collaborative problem-solving, generate instructional content, recommend personalized learning pathways, and coordinate multiple educational activities simultaneously.

This evolution also represents a conceptual shift within educational theory. Instead of viewing artificial intelligence exclusively as an external instructional resource, recent scholarship increasingly considers autonomous agents as participants within educational processes. Such a perspective extends existing discussions concerning distributed cognition and sociotechnical learning by acknowledging that learning increasingly emerges through interactions among human actors, intelligent systems, and digital infrastructures.

The conceptual framework proposed in Figure 10 synthesizes this transformation by illustrating the progression from educational technologies to adaptive learning systems, AI tutors, agentic AI, educational ecosystems, and ultimately human-AI co-learning systems. This framework extends the descriptive findings of the bibliometric analysis and provides a theoretical interpretation of how educational AI has evolved during the study period.

5.2 The Rise of Agentic AI

A second major finding concerns the rapid emergence of agentic AI as a distinct research frontier. Although intelligent tutoring systems remain an important component of the intellectual structure identified through the co-citation analysis, recent thematic developments demonstrate increasing attention to autonomous reasoning, multi-agent systems, collaborative intelligence, and autonomous decision-making.

The accelerated growth observed after 2023 corresponds closely with the widespread adoption of large language models and generative AI technologies. These innovations substantially expanded the capabilities of educational systems by enabling natural language interaction, contextual reasoning, content generation, and increasingly autonomous task execution. Consequently, research has progressively shifted from designing intelligent instructional systems toward understanding how autonomous AI agents can operate within complex educational environments.

The results further indicate that agentic AI is not merely replacing previous educational technologies but redefining their pedagogical role. Instead of functioning exclusively as tutors or assessment tools, autonomous agents increasingly support collaborative learning, facilitate knowledge construction, coordinate educational activities, and assist educators in complex instructional decision-making. This expansion of functional capabilities explains the growing prominence of concepts such as human-agent interaction, learner agency, explainability, and educational governance observed in the conceptual maps.

Nevertheless, the emergence of agentic AI also introduces new theoretical and practical challenges. Increasing autonomy inevitably raises questions regarding accountability, transparency, trust, and pedagogical responsibility. Educational institutions must therefore determine appropriate boundaries for autonomous decision-making while preserving the central role of human educators in guiding learning processes. The growing emphasis on explainable AI and ethical AI identified in the maturity phase of the keyword analysis reflects the recognition of these challenges within the research community.

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Taken together, these findings suggest that the rise of agentic AI represents a new stage in the evolution of educational artificial intelligence, characterized by increasing autonomy, collaboration, and integration rather than simple automation.

5.3 Human-AI Collaboration and Learning Ecosystems

Another important contribution of this study concerns the increasing centrality of human-AI collaboration within the literature. The thematic evolution analysis demonstrates that collaborative interaction between humans and autonomous agents has become one of the defining characteristics of contemporary educational AI research.

Earlier generations of educational technologies generally assumed relatively passive forms of interaction in which learners received individualized instructional support from intelligent systems. By contrast, recent research increasingly conceptualizes learning as a collaborative process involving continuous interactions among students, teachers, intelligent agents, institutional infrastructures, and digital learning environments.

The emergence of educational ecosystems provides an appropriate conceptual framework for interpreting these developments. Rather than viewing autonomous agents as isolated technological applications, educational ecosystems recognize that teaching and learning occur within interconnected networks of human and technological actors. Autonomous agents therefore become one component of broader adaptive systems that include learning analytics platforms, conversational interfaces, assessment systems, institutional policies, and pedagogical practices.

The bibliometric evidence further suggests that collaboration is becoming multidimensional. Human-AI interaction now extends beyond student-system communication to include teacher-AI partnerships, multi-agent collaboration, institutional decision support, and networked educational services. Such developments indicate that future educational environments are likely to depend increasingly on coordinated interactions among multiple autonomous and human actors rather than individual AI applications operating independently.

These findings also reinforce the importance of maintaining human-centred educational principles. Although autonomous agents demonstrate increasing instructional capabilities, effective educational ecosystems remain dependent upon human judgement, pedagogical expertise, and ethical decision-making. Consequently, future research should prioritize collaborative intelligence rather than technological substitution, emphasizing complementary relationships between educators and intelligent systems.

5.4 Ethical and Governance Challenges

The evolution toward increasingly autonomous educational systems also generates significant governance challenges that extend well beyond technological performance. The growing prominence of ethical AI, explainability, transparency, and learner agency within the keyword networks indicates that governance has become an integral component of contemporary educational AI research.

Autonomous agents increasingly influence instructional decisions, assessment processes, learning pathways, and student support services. As their decision-making capabilities expand, educational institutions face growing responsibilities regarding accountability, algorithmic fairness, privacy protection, and regulatory compliance. These concerns are particularly relevant because educational

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decisions frequently affect learner opportunities, academic achievement, and long-term educational trajectories.

The conceptual evolution identified in this study suggests that governance has developed alongside technological sophistication. During the emergence phase, ethical considerations occupied a relatively peripheral position within the literature. As autonomous systems became more capable and widely adopted, however, governance-related concepts progressively moved toward the centre of scholarly discussions. This pattern demonstrates that technological advancement has been accompanied by increasing recognition of the societal responsibilities associated with educational AI.

Another significant issue concerns explainability. Autonomous educational agents capable of complex reasoning and adaptive decision-making must remain understandable to educators, learners, and institutional leaders. Without sufficient transparency, educational stakeholders may struggle to evaluate AI recommendations, identify biases, or maintain appropriate levels of trust. Explainability therefore becomes a prerequisite for responsible human-AI collaboration rather than merely a desirable technical feature.

Similarly, learner agency has emerged as a central governance concern. While autonomous systems offer unprecedented opportunities for personalization and adaptive instruction, excessive automation may inadvertently reduce learner autonomy or encourage overreliance on AI-generated guidance. The challenge for future educational systems will therefore be to design autonomous agents that strengthen, rather than diminish, human intellectual independence and critical thinking.

Overall, the findings indicate that ethical governance is no longer a secondary consideration but a defining characteristic of the next generation of autonomous educational systems. Sustainable implementation will depend upon governance frameworks capable of balancing technological innovation with educational values, human oversight, institutional accountability, and learner empowerment.

Toward Human-Agent Educational Ecosystems

The findings of this study collectively support the proposition that autonomous agents in education are evolving toward integrated human-agent educational ecosystems. This evolution is characterized by simultaneous advances in technological capability, pedagogical sophistication, and governance maturity. Rather than progressing along independent trajectories, these three dimensions increasingly interact to shape the future development of educational artificial intelligence.

The conceptual frameworks proposed in Figures 10, 11, and 12 integrate the bibliometric evidence into an evolutionary model that extends beyond descriptive science mapping. Figure 10 explains the conceptual transformation from educational technologies to collaborative educational actors. Figure 11 demonstrates that technological, pedagogical, and governance developments have evolved concurrently across emergence, growth, and maturity phases. Finally, Figure 12 identifies the principal research priorities that are likely to define the next generation of autonomous educational systems, including human-AI collaboration, learner agency, explainable AI, autonomous assessment, educational governance, and lifelong learning ecosystems.

Taken together, these findings suggest that the future of educational AI will not be determined solely by increasingly powerful autonomous agents but by the quality of the relationships established between human expertise and artificial intelligence. Educational innovation is therefore likely to

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depend less on replacing teachers with autonomous systems than on designing collaborative learning environments in which human and artificial actors contribute complementary capabilities toward shared educational objectives.

6. Conclusions

This study examined the scientific evolution of research on autonomous agents in education between 2020 and May 2027 through a comprehensive bibliometric analysis of the Scopus database. By integrating performance analysis with science mapping techniques, the study identified the temporal growth, geographical distribution, intellectual foundations, conceptual structure, thematic evolution, and emerging research frontiers that have shaped this rapidly expanding field. Rather than providing only a descriptive overview of publication trends, the analysis developed an evolutionary perspective that explains how autonomous agents have progressed from intelligent educational technologies to collaborative actors within increasingly complex learning ecosystems.

The results provide a clear answer to the first research question (RQ1). Scientific production on autonomous agents in education has increased substantially throughout the study period, with a particularly pronounced acceleration after 2023. This growth coincides with the widespread emergence of generative artificial intelligence, large language models, and agentic AI, all of which have significantly expanded the educational applications of autonomous systems. The publication trajectory suggests that the field has entered a stage of rapid maturation characterized by increasing interdisciplinarity and growing international research participation.

Regarding the second research question (RQ2), the co-citation analysis demonstrates that the intellectual foundations of the field remain anchored in intelligent tutoring systems, learning analytics, educational data mining, and human-computer interaction. At the same time, newer knowledge clusters centred on generative AI, explainable AI, human-AI collaboration, and autonomous educational agents have become increasingly influential. These findings indicate that the field is simultaneously consolidating its historical foundations while incorporating emerging technological paradigms.

The third research question (RQ3) focused on thematic evolution. The keyword co-occurrence maps and thematic evolution analysis reveal a progressive conceptual transformation occurring across three distinct developmental stages. The emergence phase was characterized by technological experimentation involving artificial intelligence, adaptive learning, and intelligent tutoring systems. During the growth phase, research expanded toward personalized learning, autonomous agents, reinforcement learning, and human-agent interaction. Finally, the maturity phase has become increasingly oriented toward agentic AI, educational ecosystems, explainable AI, learner agency, lifelong learning, and ethical governance. Collectively, these findings demonstrate that the field has evolved from technology-centred innovation toward more comprehensive educational and sociotechnical perspectives.

The fourth research question (RQ4) examined the emerging research frontiers shaping future developments. The bibliometric evidence indicates that human-AI collaboration, multi-agent educational systems, autonomous assessment, educational governance, explainable AI, and learner agency represent the principal directions of future research. These themes suggest that the next generation of educational AI will increasingly focus on collaborative intelligence rather than simple

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automation, emphasizing complementary relationships between human educators and autonomous systems.

Theoretical Contributions

This study makes several theoretical contributions to the literature on artificial intelligence in education.

First, it proposes an **evolutionary model of autonomous agents in education**, demonstrating that the field has progressed through successive stages of technological experimentation, educational integration, and the emergence of agentic learning ecosystems. This evolutionary perspective extends existing bibliometric studies by explaining not only how the field has expanded but also how its conceptual foundations have changed over time.

Second, the study introduces the concept of a **transition from educational technologies to educational actors**. The bibliometric evidence indicates that autonomous agents are increasingly viewed as active participants in educational processes rather than passive technological tools. This conceptual shift provides a useful theoretical lens for understanding the changing role of artificial intelligence within contemporary educational environments.

Third, the study develops an **integrated framework of human-agent educational ecosystems**, synthesizing technological, pedagogical, and governance dimensions into a coherent conceptual model. By linking science mapping results with broader educational theory, the proposed framework moves beyond descriptive bibliometric analysis and contributes to ongoing discussions concerning the future relationship between humans and intelligent systems in education.

Practical Implications

The findings also have important implications for educational practice and policy.

For higher education institutions, the results emphasize the importance of developing strategic frameworks for the responsible integration of autonomous agents into teaching, assessment, academic support, and institutional decision-making. Universities should prioritize governance mechanisms that promote transparency, accountability, and pedagogically meaningful applications of AI.

For educators, the findings suggest that autonomous agents should be viewed as collaborative instructional partners capable of supporting personalized learning, formative assessment, feedback generation, and administrative efficiency. However, successful implementation requires maintaining meaningful human oversight and preserving the central pedagogical role of teachers.

For policymakers, the rapid evolution of autonomous educational systems highlights the need for comprehensive regulatory frameworks addressing ethical AI, data privacy, algorithmic fairness, explainability, and institutional accountability. Educational policies should encourage innovation while ensuring that AI adoption remains aligned with educational values and learners' rights.

Finally, for developers of educational technologies, the results underscore the importance of designing human-centred AI systems that enhance learner autonomy, support collaborative knowledge construction, and facilitate transparent human-AI interaction rather than replacing educational professionals.

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Future Research Directions

The rapid evolution of autonomous agents in education opens several promising avenues for future investigation.

Future research should examine how collaborative human-AI learning environments influence student engagement, critical thinking, creativity, and long-term learning outcomes. Additional studies are also required to evaluate the pedagogical effectiveness of multi-agent educational systems operating across different educational levels and disciplinary contexts.

Explainable AI represents another important research priority. As autonomous educational agents assume increasingly complex instructional responsibilities, greater attention should be devoted to developing transparent decision-making processes that enable educators and learners to understand, evaluate, and appropriately trust AI-generated recommendations.

The governance of educational AI also requires continued investigation. Future studies should explore regulatory models capable of balancing technological innovation with ethical responsibility, privacy protection, institutional accountability, and learner agency. Comparative international studies may provide valuable insights into how different educational systems approach these challenges.

Further research should investigate autonomous assessment systems, lifelong personalized learning ecosystems, adaptive educational governance, and the integration of autonomous agents within hybrid and online learning environments. The growing convergence between generative AI, learning analytics, educational robotics, and multi-agent architectures also presents opportunities for interdisciplinary research that extends beyond traditional boundaries of educational technology.

Finally, longitudinal bibliometric analyses incorporating multiple databases, citation dynamics, and collaboration networks would further strengthen understanding of the long-term evolution of autonomous agents in education and provide a more comprehensive perspective on the global development of the field.

Final Remarks

The evidence presented in this study demonstrates that autonomous agents are no longer confined to experimental intelligent tutoring technologies. Instead, they are rapidly evolving into collaborative pedagogical infrastructures capable of reshaping teaching, learning, assessment, and educational governance. This transformation reflects a broader shift in the relationship between humans and artificial intelligence, in which educational value increasingly emerges through collaboration rather than automation alone.

As educational systems continue to adopt increasingly autonomous and agentic forms of artificial intelligence, the central challenge will not be determining whether these technologies can perform educational tasks, but rather how they can be integrated responsibly into human-centred learning ecosystems that promote equity, transparency, learner agency, and meaningful educational outcomes. The future of education is therefore likely to depend not on replacing human expertise with intelligent machines, but on fostering productive partnerships between educators, learners, and autonomous agents within collaborative educational ecosystems.

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