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Can Blockchain Decentralize Education? A Systematic Review of Challenges and Pathways

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ABSTRACT

Context: The blockchain technology has become a secure, transparent, and decentralized infrastructure in data handling and its potential in the education sector has gained more and more attention especially in securing academic records, preventing credential fraud, and enhancing confidence in the verification procedures. Nonetheless, regardless of this interest, there is a lack of synthesis of the way in which blockchain is being implemented into real educational environment and the challenge that hinder its use.

Objectives: The objective of this study is to conduct a systematic review of applications of blockchain in education, determine the main areas of its implementation, evaluate the advantages and limitations mentioned in the literature, and offer recommendations to subsequent research and real-world implementation.

Methods: The systematic literature review was carried out according to the methodology suggested by Okoli and Schabram. A total of 64 peer-reviewed studies published between 2017 and 2025 were analyzed.

Results: The results showed that blockchain is mostly utilized in credential and certificate management, microcredential and credit transfer, competency and assessment tracking, and secure collaborative e-learning, with other applications in copyright protection and decentralized examination systems. Compared with conventional educational technologies, blockchain enables tamper-evident records, independently verifiable credentials, and reduced verification costs through cryptographic auditability and decentralized trust.

Contributions: This review provides a consolidated evidence base on blockchain-enabled education, highlighting realistic implementation opportunities, such as QR-hash diplomas and inter-institution credit exchanges, while emphasizing the need for privacy-preserving architectures and shared governance standards. The findings support researchers, practitioners, and policymakers to assess and promote safe, reliable, and effective blockchain-based learning ecosystems.

1 | Introduction

Blockchain is a technology that facilitates the creation of the cryptocurrency Bitcoin, providing a way to keep track of transactions on a distributed ledger that is programmed to be immutable across thousands of nodes [1]. Blockchain is a peer-to-peer technology that uses cryptography to distribute and store data [2]. Some of the educational institutions have been adopting blockchain technology, and the majority of such universities are

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employing it for the purpose of summative assessment for academic degree management and education. Blockchain is a peer-to-peer technology with a distributed, cryptographically secured data store that is an incremental log of transactions in the form of cryptography-protected blocks, linked together and replicated across multiple nodes, using a consensus mechanism [3–5]. The Joint Research Center (JRC) research report [6] states that blockchain offers ownership of learning, including ownership of coursework, feedback, and qualification. It does not require an education institution to govern ownership of learning. Blockchain technology is versatile and has lots of applications in various domains including the education sector, business world, healthcare, and government entities, due to the transparency and security offered by blockchain in these areas [7, 8]. In the current era, blockchain technology is a prominent topic in education, providing the right solution to various problems. Several colleges are implementing certificate management systems on the blockchain. There are other educational institutions that join blockchain projects such as Sony Global Education, where student records are securely stored [9]. Blockchain technology has shown significant potential in sectors like healthcare and record keeping, primarily due to its distinctive features, immutability, decentralized nature [1], and ledger system. Blockchain is being used in education to streamline the process of credential attestation, thereby minimizing the amount of time and resources needed to verify credentials [10].

In the healthcare sector, blockchain tackles the difficulty of handling massive volumes of data, such as daily patient monitoring records and medical histories [11]. Healthcare is a data-intensive domain, generating a large amount of data, including daily patient monitoring and producing medical records. Blockchain applications have been developing ledgers that include virtual tokens, which are emerging in the medical domain. It is essential to research blockchain technology merged with the system for smart contracts to equip solutions for the healthcare domain. Blockchain applications manage the intensive data of health care stored on the decentralized servers [12]. Degree verification attestation in education is a complex process, often involving manual authentication between the universities and administration department [13, 14]. The universities attest the degree and seal stamp first and then verify the administration department. This process poses serious challenges to the integrity of educational information. Blockchain technology could potentially address these authentication issues by automating and securing the verification process [15].

This study presents different applications of blockchain, advantages, and challenge to reshaping the education system. A wide range of blockchain applications are being applied in education, moving education out of the traditional domain to the digital space. No complete study has so far been done to talk about these applications in education. This systematic study aims to fill this gap by offering an in-depth exploration of blockchain-based applications and discussing the benefits and adoption challenges. The three key themes are discussed in this study, each of which exhaustively explores the blockchain-based application and explains the advantages of adoption challenges in this study. It reveals perspectives of how blockchain applications can be implemented in educational establishments in the future and gives future research work directions. Nevertheless, the current literature is still inconsistent and, instead of generalizing the real-life implementation problems and practical solutions, concentrates on technical feasibility or on single instances of use. Such ambiguity leaves the educational stakeholders, where and how blockchain can be effectively introduced and what challenge need to be overcome. Thus, the purpose of this review is to summarize evidence, determine feasible barriers to adoption, and offer systematic advice to researchers and practitioners. Figure 1 provides an overview of the study structure. Step 1 outlines the study design, formulating the research questions, developing and refining the search strategy, and setting the inclusion/exclusion criteria. Step 2 describes how 3000 initial records were screened and appraised for quality and synthesized into the 64 primary studies used for analysis. Finally, Step 3 discusses the results and classifying applications, benefits, and challenges; practical guidance; conclusions; future research directions; and limitations.

The main contributions of this study are as follows:

- Organizes and standardizes blockchain in education, such as credential management, credit transfer, competency assessment, and decentralized exams.

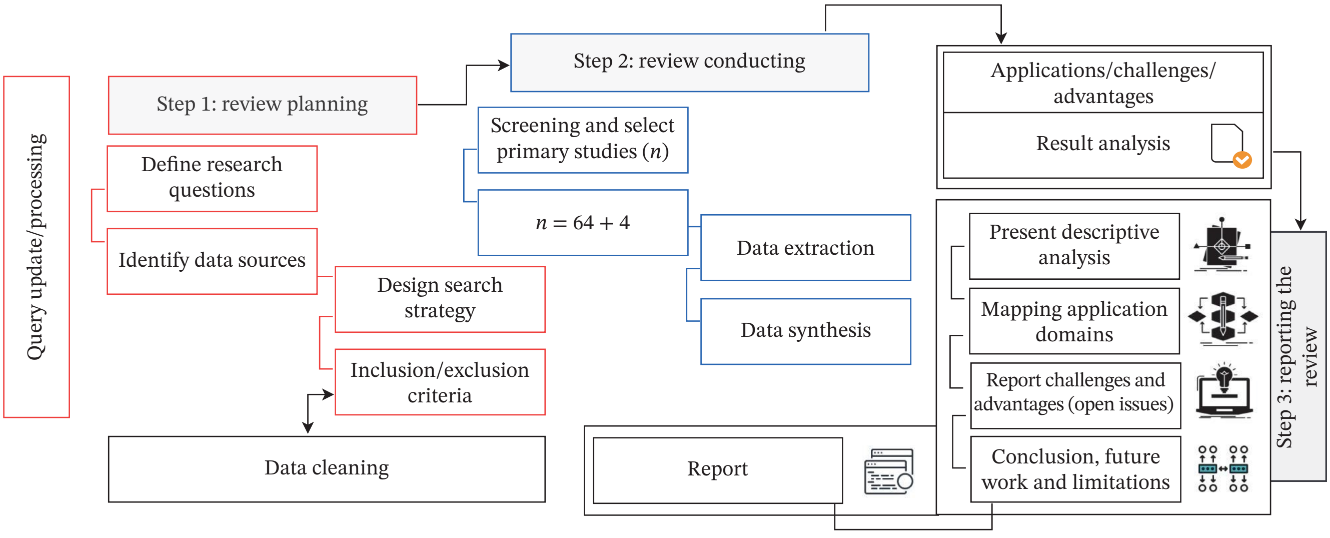

FIGURE 1 | Overview of the study structure.

- Makes a comparison between blockchain, AI, and Big Data in terms of data security, cost reduction, and transparency of trust.
- Lists six adoption issues (data privacy, immutability, usability, scalability, skills gaps, and cost of integration) and possible solutions.
- Offers practical implementation plans based on actual systems like Sony Global Education, Parchment, and EduCTX.
- Provides future-research directions, such as scalability, transaction costs, and comparison of the private and public blockchains.

2 | Methodology

This study, conducted by Okoli and Schabram [16], served as the foundation of our review. We searched IEEE Xplore, ACM Digital Library, Springer Link, ScienceDirect, and Web of Science for 2017–2025 using Boolean strings targeting education-specific applications, benefits, and adoption challenges. Inclusion includes peer-reviewed English-language studies reporting empirical evidence, case implementations, or substantive frameworks specific to education. Exclusion includes non-education, non-peer-reviewed items, opinion/editorials, and duplicates. Quality screening assessed relevance to RQs, methodological clarity, contribution, and recency of 3000 records; 2850 were excluded at title/abstract, some duplicates were removed, 100 full texts were screened, and 64 articles were included for synthesis.

2.1 | Research Questions

The subsequent research questions were developed based on the goal of this study.

1. What are the potential applications of blockchain in education?
2. What are the unique benefits of blockchain compared to other emerging technologies in the education sector?
3. What challenges are associated with the adoption of blockchain in education?

2.2 | Search Strategy

This study utilizes major scientific databases, such as IEEE Xplore, Springer, ACM Digital Library, and ScienceDirect. These databases were chosen because they contain vast amounts of high-quality and peer-reviewed articles in the fields of technology, education, and information systems, and they are very relevant to the study of blockchain in the educational environment. To find all of these studies, the search strategy developed was to create a sequence of keyword combinations that would catch a wide spectrum of research related to blockchain applications, benefits, and challenges in the education sector [16]. Such keywords as blockchain and education, blockchain applications in education, blockchain benefits in education, and blockchain adoption issues in education were used in the search as the primary ones. A search was then narrowed down by adding Boolean operators (AND and OR) which helped to include all studies relevant to the search [16]. Preliminary search yielded 3000 articles and these were reduced using title and abstract to relevant articles to the research questions. After the finial screening, 64 articles were selected to perform this study and rest articles are included for discussion only.

2.3 | Search Keywords

The search strategy covers our systematic review comprehensively on the topic of blockchain in education. An illustrative list of search strategies and keywords for the systematic review is listed in Table 1. These search keywords have been developed in such a manner that they can record diverse dimensions in the application of blockchain in education, particularly in its application [16]. This kind of keyword query helps to search for relevant studies that answer the defined research questions [16].

2.4 | Searches in Databases

Table 2 illustrates some of the databases utilized in our research on the area of blockchain in education. Table 2 classifies key electronic databases such as Web of Science, IEEE Xplore, ACM Digital Library, Springer Link, and ScienceDirect based on the query strings for the investigation of paper titles, keywords, and abstracts. This structure facilitates conducting systematic searches across scholarly platforms [16]. Table 2 is given later in this study.

2.5 | Inclusion and Exclusion of Articles

The stage of inclusion and exclusion of articles involves identifying the appropriate publications crucial for addressing the research questions. In this respect, a working list of inclusion and exclusion criteria has been developed as outlined in Table 3 [16].

2.6 | Quality Screening Process

Each study that passed the inclusion/exclusion screening was assessed against five quality criteria: (1) relevance to at least one of the three research questions, scored 0–2; (2) methodological clarity, scored 0–2; (3) originality of contribution, scored 0–2; (4) recency and contextual currency, scored 0–1; and (5) completeness of reporting, scored 0–1. Studies were required to achieve a minimum aggregate score of 6 out of 8 for inclusion. Borderline cases, defined as studies scoring between 5 and 6, were reviewed by a third author acting as arbitrator, and a consensus decision was reached through discussion.

To address potential selection bias, the search was conducted across five major academic databases with no restriction on

TABLE 1 | Search query and keywords.

Searching by query string	Searching by keywords
([Blockchain and application* and education] or [blockchain and benefits and education] or [blockchain and challenges* and education])	1. Application of blockchain in education 2. Benefits of blockchain technology in education 3. Blockchain adoption challenges in education

TABLE 2 | Electronic databases.

Electronic database	Query strings	Web address
Web of Science	Paper title, keywords, abstract	https://www.webofscience.com
IEEE Explore	Paper title, keywords	https://ieeexplore.ieee.org
ACM Digital Library	Paper title, keywords	https://dl.acm.org
Springer Link	Paper title, keywords	https://link.springer.com
Science Direct	Paper title, keywords	https://www.sciencedirect.com
Other sources	Paper title, keywords	Various additional electronic database repositories relevant to blockchain research in education

TABLE 3 | Inclusion and exclusion of articles.

Criteria for inclusion	Criteria for exclusion
Language: only studies published in English were included to ensure accessibility and consistency in language	Non-English publications: articles not published in English were excluded to maintain language consistency and accessibility
Availability: full-text articles that were openly accessible or available through institutional access were included to allow for a thorough analysis	Editorials and opinion pieces: editorial comments, opinion articles, and brief reports were excluded, as they typically lack rigorous research methodology
Publication type: only peer-reviewed journal articles, conference papers, and workshop publications were considered, as these sources are likely to meet quality standards	Irrelevant studies: studies that did not address blockchain applications, benefits, or challenges specific to education were excluded. These included papers focusing on blockchain in unrelated domains or general discussions of blockchain technology without an educational context
Topic relevance: studies had to focus specifically on blockchain applications, benefits, or challenges in the context of education. Articles that discussed blockchain broadly without a clear educational focus were excluded	Duplicate studies: duplicate publications or studies with significant content overlap were removed to avoid redundancy
Study contribution: priority was given to studies that presented empirical data, case studies, or significant theoretical contributions to understanding blockchain in education [16]	

publication venue beyond peer review status. Publication bias was mitigated by including conference papers alongside journal articles, acknowledging the rapid-publication norms of the blockchain research community. Geographic and linguistic bias is acknowledged as a limitation, as the review was restricted to English-language publications, potentially excluding relevant work published in other languages.

2.7 | Data Extraction

The data extraction was demonstrated in Table 4, which mainly concentrated on blockchain applications, benefits, and challenge to adoption in education. The extracted data was sourced from the important shortlisted articles in these aspects. Subsequently, the data was then analyzed, which included blockchain application, benefits, and challenges of adoption discussed in 64 major articles covered in [16].

TABLE 4 | Method of data extraction.

Data item	Explanation
Title	Title of the paper
Type	Conference/journal/workshop
Date	Years of publication
Language	English papers
Application	Blockchain potential applications in education
Benefits	Benefits of blockchain technology in education
Adoption challenges	Challenges of implementing blockchain in education

3 | Comprehensive Review Method and Analysis

The search was done in a comprehensive manner in six scientific databases and a total of 3000 articles were retrieved. The preliminary screening was done through the title and abstract of the articles. A significant number of articles (2850) were not included because they did not focus on the application, benefits, and adoption difficulties of blockchain in education. Next, from the remaining 150 articles, some were found to be duplications and eliminated. The articles were screened and 100 articles were chosen for in-depth reading. During the complete reading of articles, some articles were excluded due to incomplete data. Ultimately,

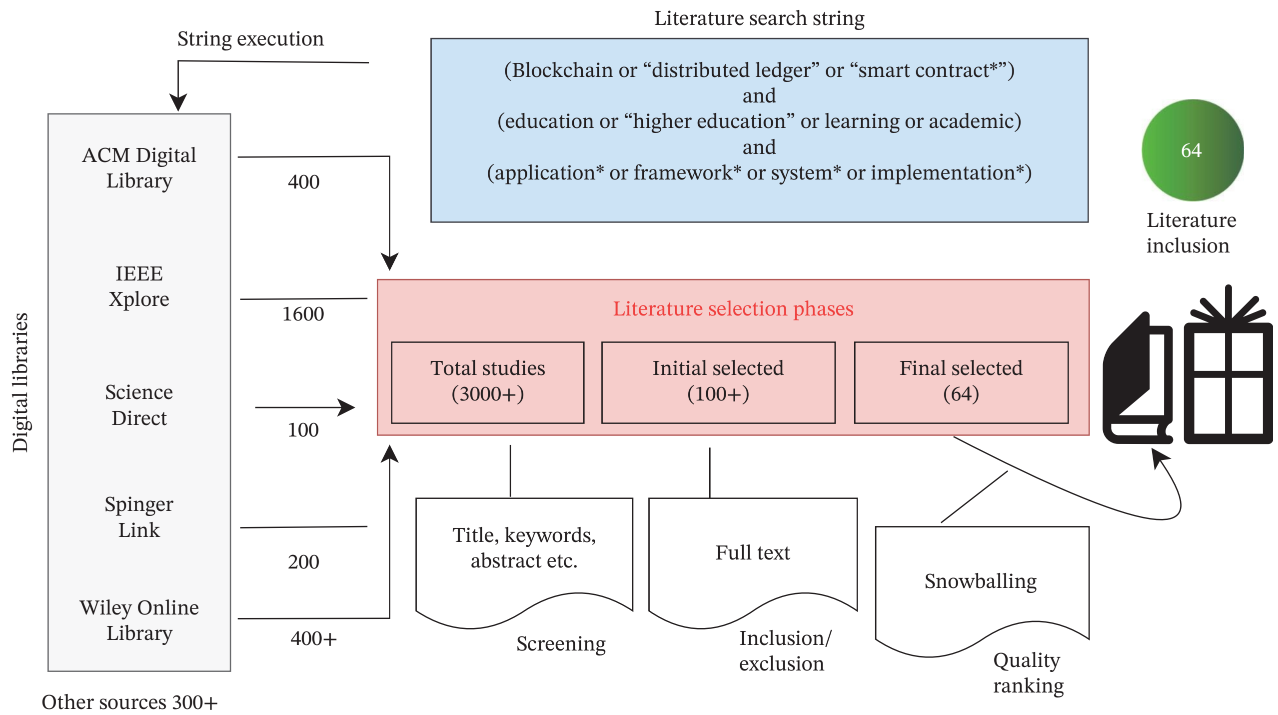

FIGURE 2 | Flowchart of the systematic review process.

64 articles met the inclusion criteria for this systematic review and went through the data extraction process. A detailed description of the review process can be found in the flow chart, as shown in Figure 2.

3.1 | Overview of Publication Years and Geographic Distribution

An overview based on publication years and geographic distribution is depicted in Figures 3 and 4. All articles included in this study have been published within the past 8 years and some others for discussion, underscoring the recent surge in relevant publications. The publication graph shows the highest number of publications (21) in 2018; more papers were published that year.

Figure 4 illustrates the geographical distribution of the collected articles. The publications come from China (20%, $N = 10$), India (12%, $N = 6$), and the USA (8%, $N = 4$). In particular, China and India rank high in publication volume, with 10 articles in China and six in India. Other countries published one article each, while some published three articles.

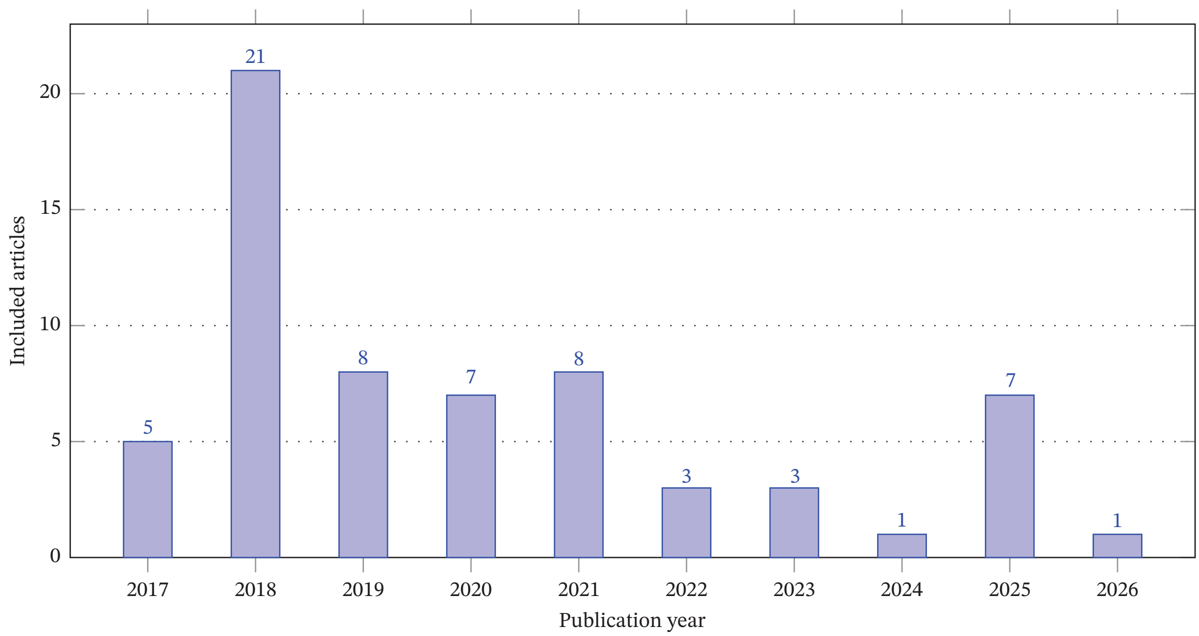

FIGURE 3 | Publication year included articles.

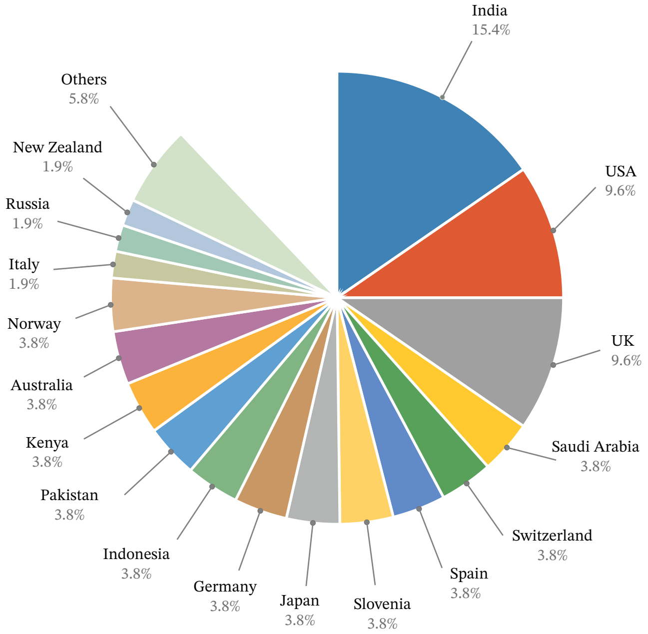

FIGURE 4 | Geographic distribution of the included studies.

3.2 | Distribution of Articles by Publication Venues

Figure 5 represents the articles' distribution by publication venue. The publications are categorized based on their focus: approximately 60% are technical, addressing subjects in engineering, technology, or computer science, while the remaining 40% are educational venues, concentrating on learning technologies or education more broadly. All included conference papers were subjected to the same rigorous five-criterion quality screening process applied to journal articles, ensuring that only studies meeting the defined quality threshold were retained for synthesis, irrespective of their publication venue. The evidence strength ratings presented in Table 5 provide a transparent and study-level account of the quality of the evidence base across all included studies.

3.3 | Integration of Blockchain With Education

Figure 6 describes the blockchain integration role in education. The development of various blockchain-based applications is giving the perspective of advantages and challenges during the adoption of blockchain in education.

3.3.1 | Blockchain Applications in Education

Most researchers have focused on evaluating students' professional competency through blockchain technology applications in education, with a total of five articles published in this category. The second most researched categories, with four articles each, are securing collaborative learning environments and secure digital certificates. The third category, with three articles each, includes credit platforms and educational evaluation and digital transfer of credentials and course credits. Certificate management, protect educational learning objects (ELOs), record management system, and permission blockchain verifying educational credentials, each have two articles. The categories with one article each include education service and payment, decentralized examination platform, enhancing student interaction in E-learning, copyright management system, students' data consent and privacy in schools, diploma management system, and issuing and validating degree apprenticeship (Figure 6).

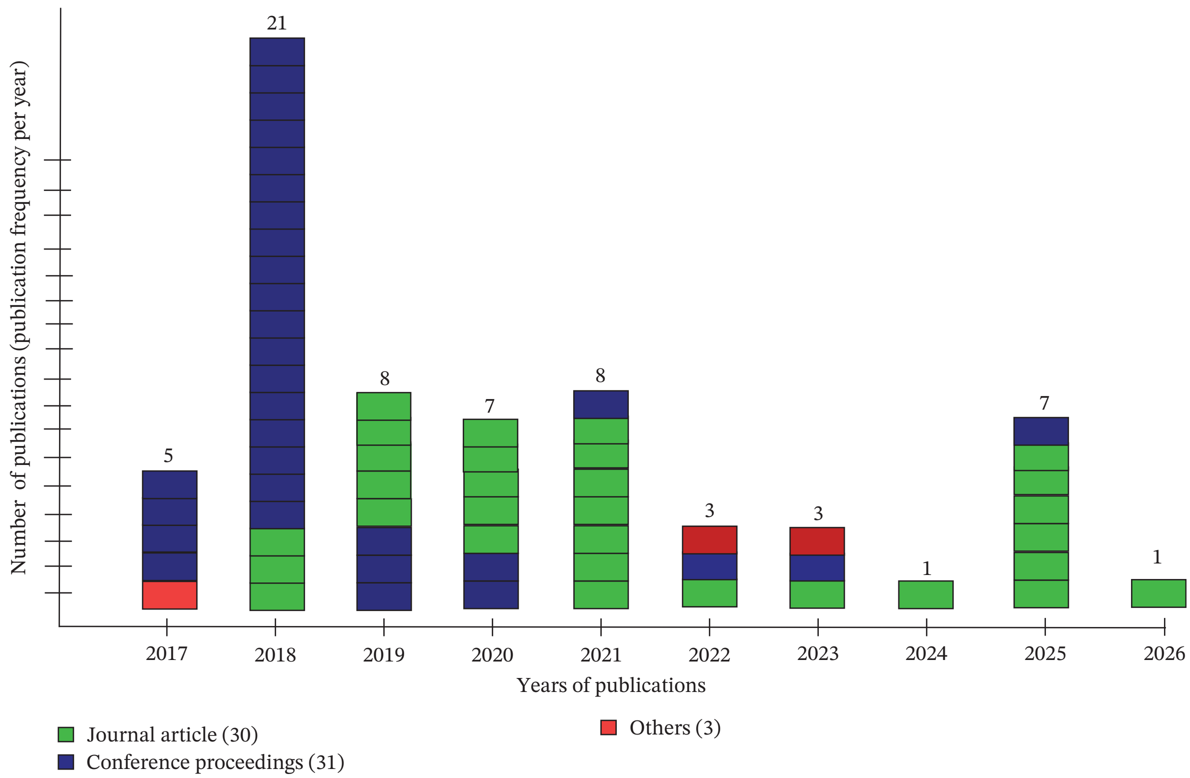

FIGURE 5 | Distribution of articles by publication venues.

TABLE 5 | Evidence summary by study type and application domain.

#	Authors	Year	Study type	Application domain	Methodology	Evidence strength
1	Xu et al. [17]	2017	Conference	Certificate management	System implementation	Medium
2	Duan et al. [18]	2017	Conference	Certificate management	System design	Medium
3	Aldowah et al. [19]	2017	Conference	Record management	Conceptual framework	Low
4	Turkanovic et al. [20]	2018	Journal	Credit platform	Prototype/system design	High
5	Chen et al. [21]	2018	Journal	Secure certificate	Design study	High
6	Bdiwi et al. [22]	2018	Conference	Collaborative learning	Framework proposal	Medium
7	Han et al. [23]	2018	Conference	Record management	System design	Medium
8	Gilda and Mehrotra [24]	2018	Conference	Student data privacy	Prototype	Medium
9	Hori et al. [25]	2018	Conference	Copyright management	System design	Medium
10	Gresch et al. [26]	2018	Conference	Certificate management	Architecture proposal	Medium
11	Farah et al. [27]	2018	Conference	Collaborative learning	Blueprint/framework	Medium
12	Bandara et al. [28]	2018	Conference	Degree apprenticeship	Architecture design	Medium
13	Arenas and Fernandez [29]	2018	Conference	Permission verification	System implementation	Medium
14	Hepp et al. [9]	2018	Journal	Certificate management	System implementation	High
15	Ocheja et al. [30]	2018	Conference	Record management	Platform design	Medium
16	Hoy [8]	2017	Conference	Credit platform	Ecosystem design	Medium
17	Wu and Li [31]	2018	Conference	Credit platform	System design	Medium
18	Liu et al. [32]	2018	Conference	Student competency	System design	Medium
19	Shen and Xiao [33]	2018	Conference	Decentralized examination	System implementation	Medium
20	Mikroyannidis et al. [34]	2018	Conference	Educational service	Framework design	Medium
21	Zhong et al. [35]	2018	Conference	E-learning interaction	System design	Medium
22	Kuvshinov et al. [36]	2018	Conference	Collaborative learning	System design	Medium
23	Srivastava et al. [37]	2018	Conference	Digital credential transfer	Framework design	Medium
24	Zhao et al. [38]	2018	Conference	Protect learning objects	System design	Medium
25	Alladi et al. [39]	2019	Journal	E-learning interaction	Review/framework	High
26	Mitchell et al. [40]	2019	Conference	Decentralized examination	System implementation	Medium
27	Alammary et al. [41]	2019	Journal	Blockchain adoption	Systematic review	High
28	Shah et al. [42]	2019	Conference	Usability/adoption	Review study	Medium
29	Hameed et al. [43]	2019	Journal	Certificate management	Review study	High
30	Haugsbakken et al. [44]	2019	Journal	Skills/adoption	Empirical study	High
31	Steiu [45]	2020	Journal	Blockchain adoption	Review study	High
32	Kosmarski [46]	2020	Journal	Usability/adoption	Empirical study	High
33	Lizcano et al. [47]	2020	Journal	Student competency	Empirical study	High
34	Bhumichitr and Channarukul [10]	2020	Conference	Certificate management	System implementation	Medium

(Continues)

#	Authors	Year	Study type	Application domain	Methodology	Evidence strength
35	Khan et al. [15]	2021	Journal	Certificate management	System design	High
36	Manoj et al. [48]	2021	Journal	Digital credential transfer	System design	High
37	Kassab et al. [12]	2021	Journal	Record management	Systematic review	High
38	Loukil et al. [49]	2021	Journal	Blockchain adoption	Systematic review	High
39	Duwadi [50]	2021	Journal	Blockchain adoption	Systematic review	High
40	Patil et al. [4]	2021	Conference	Decentralized examination	System design	Medium
41	Guustaaf et al. [51]	2021	Journal	Certificate management	Review study	High
42	Bjelobaba et al. [52]	2023	Journal	Student competency	Empirical study	High
43	Rahman et al. [53]	2023	Conference	Certificate management	System implementation	Medium
44	Sudaryono et al. [2]	2020	Journal	Student assessment	System implementation	Medium
45	Sasikumar et al. [3]	2023	Book Chapter	IoT security	Conceptual analysis	Low
46	Cheng et al. [5]	2025	Journal	Smart classroom evaluation	Experimental study	High
47	Grech and Camilleri [6]	2017	Report	Education policy	Descriptive study	Low
48	Yumna et al. [7]	2019	Conference	Blockchain in education	Systematic review	High
49	Agbo et al. [11]	2019	Journal	Healthcare blockchain	Systematic review	Medium
50	Razzaq et al. [13]	2025	Journal	Online certification/Web3	System implementation	High
51	Jumani et al. [14]	2022	Book Chapter	VR/AR education	Conceptual study	Low
52	Lan et al. [20]	2025	Conference	Data verification	System design	High
53	Sharma and Batth [54]	2020	Conference	Blockchain adoption	Review study	Medium
54	Duwadi [50]	2021	Journal	Blockchain in education	Systematic review	High
55	Mirbahar and Kumar [43]	2025	Journal	AI-based recommendation	Empirical study	High
56	Mehammed et al. [55]	2025	Journal	Data security/federated learning	System design	High
57	Holbl et al. [40]	2018	Conference	Microcredentials	System implementation	Medium
58	Ortiz-Garcés et al. [56]	2024	Journal	Cybersecurity education	AI-based system	High
59	Chaudhry et al. [57]	2022	Conference	AI in education	Framework design	Medium
60	Florea and Florea [58]	2020	Journal	Data privacy	Conceptual analysis	Medium
61	Hapuarachchi et al. [59]	2025	Journal	Cybersecurity education	Empirical study	High
62	Shaikh et al. [60]	2022	Journal	Blockchain accreditation	System design	High
63	Alwakid and Dahri [61]	2026	Journal	Gamified learning	Empirical study	High
64	Shah and Raj [62]	2025	Journal	Blockchain Infrastructure (CBDC)	Analytical study	Medium

Note: Evidence strength criteria: high: peer-reviewed journal article reporting empirical results, a fully implemented and evaluated system, or a systematic review. Medium: conference paper reporting a working prototype, validated framework, or design study with partial evaluation. Low: conference or workshop paper presenting a conceptual proposal without empirical validation or system implementation.

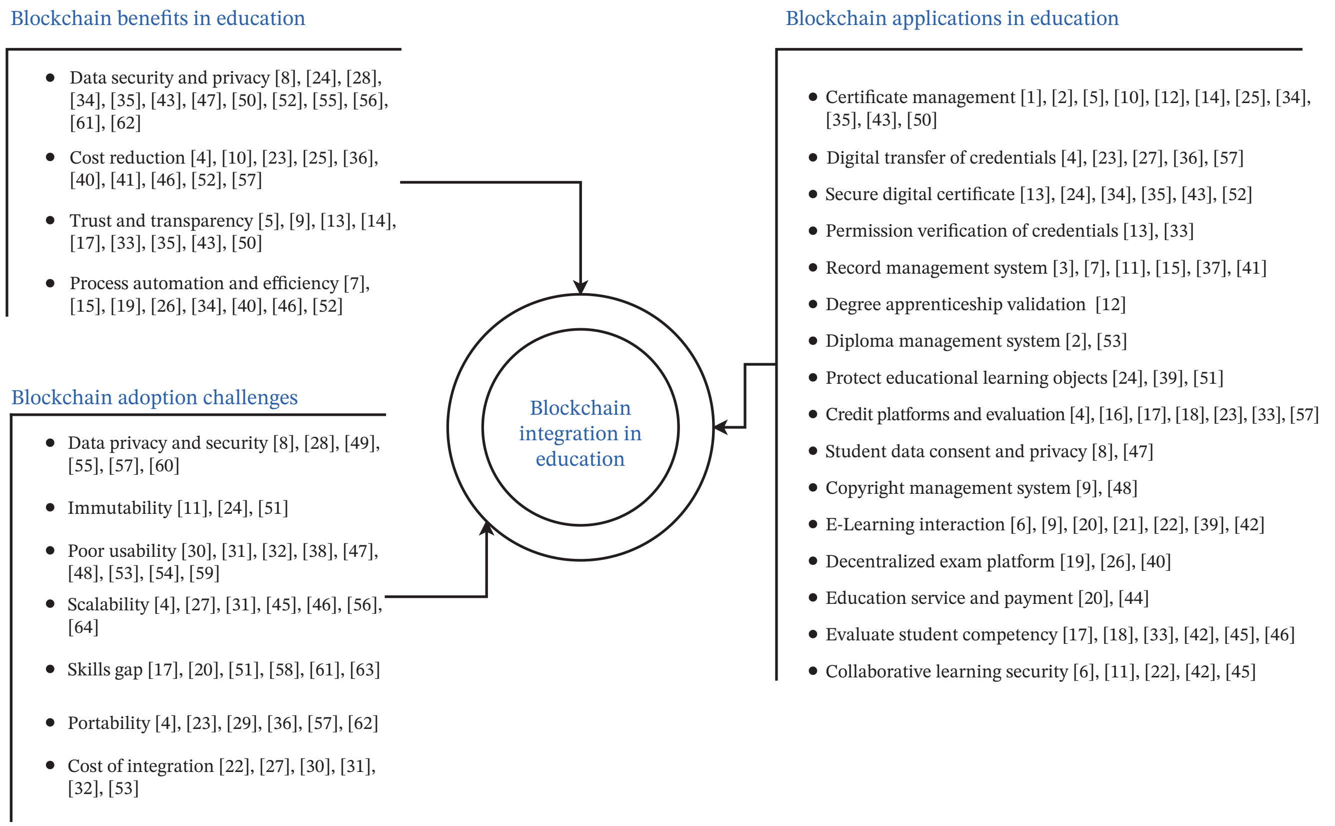

FIGURE 6 | Blockchain integration in education applications, benefits, and challenges.

3.3.2 | Blockchain Benefits in Education Compared to Other Emerging Technologies

The review articles identified three key benefits of blockchain in education, as illustrated in Figure 6. The first advantage is that it improves data security and privacy, which is crucial considering the significance of securing educational content. Two articles explicitly explain this advantage of blockchain, and two other articles make a comparison with other technologies. The second advantage is a reduction in costs due to the blockchain technology; two articles have been published that discuss the advantage. The third advantage is trust, where blockchain offers immutable record management, which means that once a blockchain has been recorded, it can never be changed. One article has focused on this advantage, comparing it to the other two.

3.3.3 | Blockchain Adoption Challenges in Education

The review articles identified six different types of challenges (Figure 6). The first issue relates to the cost of implementing blockchain to the education process, and one of the articles is dedicated to this point. The second challenge, as highlighted by the researcher, is the inadequate skills to handle blockchain technology, and one of the articles covers that. The third challenge revolves around the scalability challenges, with one article focusing on the difficulties in managing blockchain transactions on scale. This is a critical issue, and it needs to be handled by excellent individuals to handle blockchain transactions. This challenge was covered in two articles. The fourth challenge is the lack of usability, the most talked about, as five articles emphasize the necessity to improve the user experience to make blockchain adoption in education easier. The fifth issue is connected with immutability which is a major feature of blockchain, according to which data that are recorded cannot be changed, and one article has been published on the matter. Lastly, the issue of data privacy and security is also rather important with two articles covering the difficulties of ensuring safety and confidential transactions of the blockchain. These issues are classified as data privacy and security, immutability, poor usability, scalability, skill requirements, and cost issues. Each of the challenges related to implementing blockchain in education has been discussed by different researchers.

4 | Discussion

The research trend reflects a growing global demand for blockchain technology in education, with institutions increasingly recognizing its potential to improve security, transparency, and efficiency across academic and administrative functions. In this review study, we address three research questions. The systematic review discusses each research question individually, providing valuable insights.

4.1 | What Are the Potential Applications of Blockchain in Education?

The first research question examines the potential applications of blockchain in education, as summarized in Table 6 and Figure 7. The reviewed studies explore how blockchain can improve efficiency, security, and reliability across educational processes, and giving solutions to secure the certificate, data privacy, and credential verification.

TABLE 6 | Blockchain application in education.

Application	Explanations	Cross-study insight
Certificates management	The research by Xu et al. [17] explores a blockchain solution aimed at enhancing the privacy and efficiency of education certificate management and introduces a high-performance education certificate blockchain (ECBC) with an efficient query. In their research, Rahman et al. [53] designed a blockchain-based verification method for academic certificates. This system is used to ensure genuineness, and it corrects errors during certificate generation. This research provides a solution for school administration in dealing with the challenges of certificate generation. According to Lan et al. [20], a blockchain-based method was designed to secure the academic data	Across the nine studies addressing certificate management, there is strong convergence on hash-based verification and QR code delivery mechanisms. However, studies diverge on whether public or permissioned blockchains are more appropriate, reflecting unresolved tensions between auditability and institutional privacy requirements. No study provides longitudinal evidence of adoption beyond pilot scale
	Real-world examples	
	Sony Global Education: Sony Global Education, in collaboration with IBM has developed a blockchain-based platform for securely storing the student's records and transmitting them to the different educational sectors. The platform allows educational institutions to check the learning evidence, such as diplomas and academic accomplishments, accommodate the institutions in avoiding educational data manipulation, and provide a secure and transparent assessment [9, 30, 63]	
	Edgecoin: EdgeCoin introduced the blockchain platform to solve the challenge of validating education credentials by utilizing third-party verification. The results provide significant cost savings over the traditional human-based techniques. The EdgeCoin platform streamlined the consensus mechanism that ensures the certificate results cards and students' personal information are stored on the blockchain platform [51, 54]	
	Parchment: The parchment blockchain platform supports learners throughout their academic and professional journey by providing a secure and transparent way to verify and receive their credentials. The Parchment platform, which handles over 30 million transcripts globally, exemplifies how blockchain technology can scale credential management and allow secure and transparent communication between companies, academic institutions, and students [19]	
	Diploma Management System: In their research, Gresch et al. [26], developed a blockchain-based diploma management system to eliminate credential fraud. This research introduced the preserved diplomas' authenticity and stored them into secure and transparent verification on the blockchain	
	Implementation strategy: Educational institutions successfully implement blockchain technology for certificate management by following this strategy	
	Pilot program for diploma verification: Start with a small-scale implementation, securely store student graduate certificates and verify the diplomas	
	Action: In the first phase, select a limited number of recent graduates and issue their diplomas via the blockchain platform. Ensure that these certificates are easily verified by employers and institutions	
	Benefits: With these first techniques, institutions can test the technology, functionality, and integration with a lower risk	

(Continues)

TABLE 6 | (Continued)

Application	Explanations	Cross-study insight
Digital transfer of credentials and course credits	In their research, Srivastava et al. [37] developed a blockchain-based educational framework. It received support from worldwide educational sectors such as colleges and other higher education institutions, who decided to collaborate on it. The framework provides facilities for college students to transfer their course credits and credentials between parties digitally. It facilitates the smooth transfer of students' credits across colleges and offers potential market players easy access to credit information. This method provides simplified manners for schools and universities to communicate certificates and courses. In another study by Manoj et al. [48], a blockchain credit transfer system was designed. The developed mechanism turns students' credit into tokens used in various courses. The developed system has been used at universities. When students finish their courses, they turn them into tokens and deposit them on the blockchain. This mechanism ensures the security of the student's information Real-world example Tutellus: A blockchain platform addresses students' challenges in school and college. The platform boasts an amazing 1 million users and a collection of 130,000 video courses. Tutellus has a highly fast, responsive platform for capable student traffic. Tutellus uses "sharding," which divides tasks into nodes to facilitate faster and more efficient communication. The platform utilized large databases divided into more manageable, smaller data shards. Nodes exchange data with a Directory Service (DS) committee, which combines it into a final block, with each node handling a specific task. This method maximizes the company's task capabilities, which benefit all user groups [51, 54] Implementation strategy: Educational institutions can implement blockchain for digital transfer of credentials and course credits using the following strategy Pilot program for inter-institution credit transfer: To start the pilot program, select a small consortium of partner institutions to participate in the project. The system tokenizes course credits upon completion, and records are shared on the blockchain Action: Upon course completion, a unique token is generated to represent the credit earned. Students can access their credits across institutions and the platform through a blockchain-based portal, and enable faculty administration at participants to validate credits directly from the blockchain. This strategy removes the need for centralized verification Benefits: The tokenized credit system increases efficiency and removes the administrative load and processing time. It also provides security against tampering and ensures data integrity. The students gain more control over their academic records and can transfer credits more easily between institutions	Studies in this category converge on tokenization as the primary mechanism for credit transfer. However, they diverge significantly on platform choice, with some using public Ethereum-based systems and others using permissioned Hyperledger networks. The lack of a common interoperability standard across these systems remains an unresolved gap in the literature
Secure digital certificates	In their research, Chen et al. [21] designed a mechanism for securely issuing digital certificates, and the research identified the events involving fake graduation certificates, which were often discovered due to the lack of an effective anti-forgery mechanism. This research introduces a process for developing a secure digital credential, which begins with making a digital copy of the paper certificate and storing the important information in a database.	The three studies in this category consistently identify QR codes and cryptographic hashes as the preferred implementation mechanism. However, none of the reviewed studies report large-scale deployment or independent security audits, limiting the evidence base for claims about real-world security effectiveness

(Continues)

Application	Explanations	Cross-study insight
	Additionally, the electronic file's hash value is added, and the blockchain system integrates with the hash value. The digital certificate is integrated with the QR code and an inquiry string that is generated by the system. This research secures the digital certificate generation mechanism Real-world examples APPII: APPII is a learner's credential verification platform that uses machine learning and smart contracts to verify academic backgrounds. This platform facilitates the students to create their own CVs, biographies, and educational backgrounds, and students, teachers, and educational administration may store their data on the APPII blockchain [51]. Many research studies have explored the importance of credential verification systems, including Duwadi's in-depth assessment of blockchain in education [50]. According to Mirbahar et al. [43], a mobile-based smart education system was proposed and developed using machine learning techniques, and Mehammed et al. [55] used federated learning technique and blockchain to secure the data Echolink: Echolink, "Human Capital Link Skills Education," is a blockchain-based platform that links teachers, students, and school and college administration. Echolink is an international blockchain platform that stores credentials, certificates, qualifications, and job history hashes permanently. Echolink has proved its commitment to data integrity by cooperating with Microsoft and using Azure cloud services for its blockchain applications [31] Implementation strategy: The educational institutions can successfully implement blockchain technology for secure digital certificates by following these steps Initiate a certificate verification system: Begin with a pilot project to issue digital certificates to a specific graduating class or group of students and design a digital certificate template that includes a QR code and a unique inquiry string linked to blockchain data Action: Issue each certificate digitally with a unique hash value generated from the certificate's data and store the hash value on the blockchain, linking it to the inquiry string or QR code for future verification. Create a user-friendly verification portal that allows employers and institutions to scan the QR code or input the inquiry string to authenticate the certificate Benefits: The immutability of blockchain ensures that once certificate information is stored, it cannot be altered, providing a secure solution against forgery. With QR codes and inquiry strings, stakeholders can easily verify certificates quickly and reliably, reducing the time and cost associated with manual verification	
Permission blockchain verifying educational credentials	The research by Arenas and Fernandez [29], explored the permission blockchain to verify educational credentials and certificates. The research developed the Credential Ledger System, a blockchain-based system that technique stored succinct information supporting digital academic certificates in blockchain ledgers, which made validation by the other stakeholders easy. Real-world example: Gradebase: Gradebase is a blockchain-based platform that validates educational data for utilizing Bitcoin. The Gradebase platform	The two studies in this category highlight the advantage of permissioned blockchains for protecting student privacy while enabling controlled verification access. However, both studies are limited to small-scale institutional pilots, and neither addresses the governance challenges of maintaining a permissioned network across multiple independent institutions.

(Continues)

Application	Explanations	Cross-study insight
	offers a simple and cost-effective profile system, with students' CVs updated using a QR code provided by the Gradebase system [64]. Set Up a Permissioned Blockchain Network: Start by establishing a permissioned blockchain network, restricting participation to authorized stakeholders, such as educational institutions, accrediting bodies, and selected employers. Establish roles and permissions within this network to manage who has the authority to issue, update, or verify credentials. Benefits: Controlled Access: Only verified participants are permitted to interact with credential data, ensuring security and safeguarding student privacy. Utilizing a permissioned blockchain allows institutions to reduce the costs and complexity associated with third-party verification services.	
Record management system	Han et al. [23] explains revolutionary blockchain-based methods for establishing a setting where individuals are guardians of their official educational personal information and records. This developed system allows learners and teachers to share this data easily. This research designs a solution to incorporate blockchain technologies and empower educational institutions to produce authentic certificates that prove completion or achievement Implementation strategy: To implement this system, institutions might begin with a pilot program for recent graduates, enabling them to manage their records digitally via blockchain. A decentralized record management platform would securely store records, allowing students to share their data with specific parties using permission-based smart contracts. This approach would empower students, strengthen data privacy, and enhance the efficiency of record verification for both institutions and employers	Both studies addressing record management emphasize student empowerment and data ownership as key motivations. However, they differ in their approach to access control, with one using smart contracts and the other relying on permissioned network roles. Neither study addresses the legal and regulatory implications of student-controlled records under frameworks such as GDPR
Issue and validate degree apprenticeship	In their study, Bandara et al. [28] designed a blockchain-based architecture to transform the centralized model of issuing and validating degree apprenticeship certification into a decentralized ledger of secure databases. In this research, the model is utilized in different educational institutions' distributed databases, where it is replicated and synchronized online among academic institutions, professional associations, legislative or regulatory agencies, and business associations. The blockchain model provides a secure collaborative authentication system within a decentralized topology through the exchange of trust techniques and capabilities with the blockchain Implementation strategy: Institutions could initiate a pilot program involving a select group of apprenticeship graduates and issue their certifications through a blockchain platform. Leveraging smart contracts, this system could automatically validate and grant access to verified apprenticeship credentials for relevant stakeholders, such as employers and regulatory bodies. This decentralized approach enhances trust among all parties and provides a streamlined verification process, reducing the risk of credential fraud while ensuring transparency and data integrity in certification	This application area is represented by only one study, limiting cross-study synthesis. The proposed architecture is theoretically sound but has not been empirically validated. Future research should prioritize pilot implementations involving real apprenticeship programs and regulatory stakeholders
Protect educational learning objects	In their research, Srivastava et al. [37] developed the electronic educational environment (EEE) with a single learning object bank. The research explored ways to protect the cooperative bank of learning items. This study mainly focused on the knowledge	The two studies in this category address different aspects of learning object protection, with Srivastava et al. [37] focusing on access control and Zhao et al. [38] focusing on

(Continues)

TABLE 6 | (Continued)

Application	Explanations	Cross-study insight
	objects, networks, and approaches for embedding learning objects in courses and the research importance of the need to secure and standardize educational material, especially e-learning and MOOCs (massively open online courses). In other research, Zhao et al. [38] designed a novel blockchain-based authentication solution for digital education transactions. This study examined the legitimacy of education transactions and objects kept on the blockchain platform, and this research also contributes an information model that uses smart contracts to offer authentication services Implementation strategy: Institutions need to create a secure Learning Object Bank on a blockchain network to store digital course materials like e-learning modules and MOOCs in order to implement blockchain for protecting educational learning objects. Through the use of smart contracts, the system can authenticate and manage access to these resources, ensuring only authorized users can view or edit	transaction authentication. Together they suggest a complementary architecture, but neither study addresses the scalability implications of storing large volumes of educational content on-chain
Securing collaborative learning environments	Bdiwi et al. [22] designed a blockchain-based, omnipresent, and Internet of Things-secure, decentralized-learning environment. The designed model provides security and privacy in educational content. The platform provided security and transparency in the intelligent learning environment. Another study by Zhong et al. [35] explored the use of blockchain technology in a word-learning system and addressed e-learning's drawbacks, including low user participation, incompatibility with certain systems, and security of user data. The suggested blockchain improves security and learner engagement to allay these worries Real-World Example Teachmeplease: TeachMePlease is a learning institution directory that lists both online and offline educational institutions. The diverse learning programs include a variety of educational groups for children and individual teachers. Many educational apps need significant data to carry out learning activities, and Teachmeplease offers a dedicated platform for organizing them. TeachMePlease features two primary components: private and public. The public architecture made use of the Ethereum blockchain for assignment solutions and course updates. On the other hand, personal data is stored on the private Hyperledger blockchain. Segmentation into private and public components reduces traffic and provides safe data management [29, 36, 51] Set up a dual-layer blockchain framework: Public layer (ethereum blockchain): Utilize a public blockchain to manage assignments, course updates, and shared learning materials, making them accessible to all participants Private layer (hyperledger blockchain): Implement a permissioned, private blockchain to securely store sensitive data such as student records, personal details, and private project contributions Action: Launch a pilot program for a specific course or collaborative project, enabling students and teachers to access shared resources via the public blockchain. Set up a secure user management system where students' private data is encrypted and stored on the private blockchain, ensuring access is restricted to authorized parties only. Allow real-time tracking of interactions,	The four studies in this category converge on the importance of combining public and private blockchain layers for collaborative learning environments. However, they diverge on the role of blockchain in incentivizing learner participation, with some proposing token-based reward systems and others focusing purely on security. The evidence for improved learning outcomes through blockchain-secured collaboration remains limited

(Continues)

TABLE 6 | (Continued)

Application	Explanations	Cross-study insight
	such as assignment submissions and group discussions, on the blockchain to improve transparency Benefits: The private blockchain ensures the protection of sensitive student data, while the public blockchain allows for transparent course material sharing, maintaining data integrity and privacy. This secure and organized environment encourages open collaboration, allowing students to work together confidently, knowing their data is safeguarded	
Evaluating students' professional competency	In their research, Lizcano et al. [47] investigated a blockchain-based trust model for open and widely available higher education that verifies the acquisition of student qualifications from various training institutions was investigated. This application allows the assessment of the value of participating in training facilities in a decentralized, automated, and equitable manner Furthermore, another study by Liu et al. [32] focused on coordinating information between the credit systems of incomplete university students and employer institutions. The study designed a private blockchain Hyperledger fabric. The Hyperledger blockchain platform enables universities and enterprises to share information transparently, meeting student skills and educational knowledge requirements for enterprise recruitment and current market trends. Another exploratory study by Shen and Xiao [33], an online questionnaire, collects information about higher education. The grading system in the online examination is unfair and ambiguous the results are altered. To remove the ambiguity in the online examination, the double-layer consortium blockchain introduced the mechanism by which the grading marks are securely stored on this platform. This platform provides consistent and unchanging offers and permanent solutions to store on a blockchain Additionally, Mikroyannidis et al. [34] designed smart blockchain badges for data science teaching methodologies. This researcher determined how these badges might help learners, teachers, and administration advance their careers in data science by providing individualized suggestions based on their learning achievements. The designed model seeks to improve the data science certification and maintain a transparent certification procedure. Bjelobaba et al. [52] investigated the blockchain-based application for evaluating students' work that integrates project-based learning through the blockchain platform. This methodology allows the students to improve their assessment criteria using a project-based approach Implementation strategy Institutions can leverage blockchain technology to assess students' professional competencies by developing a decentralized trust framework on platforms like Hyperledger. This model would securely record and verify student qualifications, skills, and competencies from various training programs. Using smart badges and project-based assessments on the blockchain, institutions can provide transparent, immutable records of students' achievements and skills. A double-layer blockchain structure can store grading and assessment records securely, ensuring fairness and transparency in evaluation. This approach enables seamless sharing of verified competencies with employers and aligns student qualifications with market demands	This is the most researched application category with five studies, reflecting strong research interest in blockchain-based competency verification. However, studies vary significantly in their definition of competency, ranging from formal academic qualifications to informal skill badges, limiting cross-study comparability. No study provides evidence of employer adoption or integration with existing HR systems

(Continues)

Application	Explanations	Cross-study insight
Credit platforms and educational evaluation	In their research, Turkanović et al. [63] developed a higher education global credit platform. This platform develops and creates a dependable decentralized higher education credit and rating system that provides the benefits of educational organizations and higher education institutions. In this research, the author developed the prototype for managing access to a peer-to-peer network of credit systems for students completing their courses. This platform represented more progress toward openness and efforts in the higher education sector. In another study by Hölbl et al. [40], a blockchain-based ecosystem platform was introduced to maintain the assign and display credentials to individual academic organization stakeholders. The developed platform offered digital services, including the potential for the institution to automate the evaluation of personal talents and knowledge. Furthermore, the research by Wu and Li [31], a digital operational evaluation system based on blockchain, was designed. Through this system, students participate in games, and the functional school evaluates the qualities of both students and teachers. In the digital educational era, schools used blockchain to improve cooperation, providing immutable digital certification for academic records. This research provided a blockchain-based solution for secure competition evaluation. This study designed the blockchain application method frame and examined evaluation criteria along with operational algorithm skills Implementation strategy: To establish a blockchain-based platform for educational evaluation, institutions can develop a decentralized peer-to-peer system that securely records and manages academic credits and assessment outcomes. By utilizing a global credit platform, students' course completions, achievements, and competencies can be securely and transparently documented on the blockchain. The platform can leverage smart contracts to automate the assignment of credits, evaluation of skills, and display of achievements, enabling institutions to assess students' knowledge and abilities in a streamlined, tamper-proof environment. Furthermore, blockchain ensures consistent evaluation standards across institutions, enabling secure, automated verification of credits and competencies for stakeholders, including employers and educational bodies	The three studies in this category consistently identify decentralization and transparency as the primary advantages of blockchain-based credit platforms. However, they diverge on governance models, with EduCTX proposing a consortium approach and other systems proposing fully decentralized models. The sustainability of these governance models at scale remains an open research question
Student data consent and privacy in schools	In their research, Gilda and Mehrotra [24] investigated into obtaining data consent from legal guardians and parents is limited when using traditional paper forms for human data. These methods not only lack efficiency in providing consent but also lack accountability. This problem is addressed by implementing blockchain technology, which introduces an innovative contract legal process that establishes an intelligent agreement between the school and the parents. The research used Hyperledger fabric blockchain and Hyperledger Composer to design an application enabling school administrators to contract with third-party stakeholders for legal data. Parents can rely on smart contracts to consent to data access rights Implementation strategy: To implement a blockchain solution for student data consent and privacy, schools can use Hyperledger Fabric with smart contracts to streamline and secure the consent process. Smart contracts can handle and document parental consent for data sharing, ensuring transparency and accountability.	This application area is represented by only one study, which presents a promising prototype but does not address the legal enforceability of smart contract-based consent under existing data protection regulations such as GDPR and FERPA. Future research should prioritize regulatory alignment

(Continues)

TABLE 6 | (Continued)

Application	Explanations	Cross-study insight
	This system enables parents to digitally grant or revoke data access rights, reducing paperwork and improving data privacy. Schools can securely manage and track consent agreements with third-party stakeholders, maintaining a clear, immutable record of permissions	
Copyright management system	In their research, Hori et al. [25] investigated the digital education improvement through blockchain technology. This research mainly focuses on the copyright problem in the development and dissemination of educational resources. This research developed a decentralized Chilo learning e-book system that uses blockchain to handle digital rights, content production, and sharing. This study explored the issues of copyrighted content on Chilo and created a new blockchain platform that uses virtual money Implementation strategy: To implement a blockchain-based copyright management system, educational institutions can develop a decentralized platform for managing digital rights associated with educational resources. Leveraging blockchain, this platform can securely monitor content creation, usage, and sharing, ensuring that copyright information is tamper-proof and accessible	This application area is represented by only one study, reflecting an underexplored use case in the blockchain education literature. The proposed system is technically innovative but has not been validated at scale. The intersection of blockchain-based copyright management and open educational resources represents a promising direction for future research
Enhancing the student's interaction In E-learning	In their research, Alladi et al. [39] designed a framework for an e-learning online platform focused on word learning. This platform uses blockchain to handle dispersed user engagement from people who are spread across different locations. To evaluate the qualities of the system utilizing the ISO quality methodology, the system assesses the efficiency of the overall word learning framework Implementation strategy: To enhance student interaction in e-learning, a blockchain-based framework can be implemented to securely track and manage user engagement across different locations. By utilizing blockchain, the platform can track and analyze student interactions, offering a transparent system that encourages active participation. Smart contracts can reward students for completing learning milestones, promoting engagement	This application is represented by one study, which focuses on technical efficiency rather than pedagogical outcomes. The evidence base for blockchain improving actual learning engagement as opposed to technical interaction tracking remains limited across the reviewed literature
Decentralized examination platform	In their research, Mitchell et al. [65] investigated the design of the Dapper application for test paper production and its assessment methodology. The research utilized the permissioned Hyperledger blockchain platform to provide secure and transparent distributions and audits of the methods Implementation strategy: To implement a decentralized examination platform, educational institutions can leverage a permissioned blockchain like Hyperledger to securely oversee the creation, distribution, and assessment of test papers. With blockchain, exam papers can be securely shared with authorized participants, ensuring transparency and preventing unauthorized access	This application area is represented by one study, which demonstrates technical feasibility but does not address the practical challenges of large-scale examination administration, including invigilation, identity verification, and accessibility. Future research should address these operational dimensions

(Continues)

TABLE 6 | (Continued)

Application	Explanations	Cross-study insight
Educational service and payment system	Mikroyannidis et al. [34] examined blockchain, revolutionizing lifelong learning in education. The author explores into various aspects of lifelong learning, outlining how ePortfolios, accreditation, and tutoring evolve within this learner-centered system Implementation strategy: To implement a blockchain-based educational service and payment system, institutions can develop a decentralized platform for manage payments, ePortfolios, and service registration. Blockchain can securely store student records, credentials, and transaction histories, enabling the tracking and verification of lifelong learning services like accreditation and tutoring. Smart contracts can automate payments, course enrollments, and access to educational services, improving both the efficiencies and security of these processes. This system guarantees transparency in transactions, provides tamper-proof records for lifelong learning achievements, and supports a seamless, learner-centered educational experience	This application area is represented by one study, which provides a high-level conceptual framework rather than an implemented system. The integration of blockchain-based payment systems with existing institutional financial infrastructure represents an underexplored technical challenge that future research should address

To provide a structured overview of blockchain-based applications in the context of education, the following summary is presented in the form of an overview chart (Figure 7). Figure 7 emphasizes applications for the secure and tamper-resistant storage of ELOs, trust models for the recording of student qualifications and competences, and applications that enable the use of blockchain-based credentialing mechanisms like smart badges. Student data consent and privacy management systems are examples of privacy-focused applications that can be built on permissioned blockchain platforms like Hyperledger composer, which provide controlled access to data and ensure regulatory compliance. Decentralized architectures also support the issuance and validation of degree apprenticeships, providing greater transparency and trust between the educational institutions, employers, and licensing entities. Moreover, blockchain can improve student participation in the e-learning process by letting learners know about interactions, incentivizing them to participate, and providing secure assessment via decentralized exam platforms such as Hyperledger examination and review systems.

Collaborative learning environments benefit from Ethereum and Hyperledger-powered platforms that strengthen data security, increase learner participation, and enable transparent evaluation through distributed and, in some cases, gamified learning ecosystems. Permissioned blockchain systems further support educational credential verification, secure authentication of digital learning resources, and streamlined profile validation processes. The figure also captures applications related to copyright management for educational content, the digital transfer of academic credentials and course credits through scalable and tokenized systems, and automated certificate verification using smart contracts. The use cases include evaluating students' professional competencies through global credit platforms, supporting credit-based educational evaluation systems with parental consent mechanisms, and enabling educational service and payment platforms for managing ePortfolios, accreditation, and academic transactions.

For each application shown later, an implementation strategy is provided. Each strategy specifies an action phase, a pilot scope, and measurable benefits to guide practical deployment.

4.2 | What Are the Unique Benefits of Blockchain Compared to Other Emerging Technologies in the Education Sector?

The second research question examines the unique benefits of blockchain compared to other emerging technologies in education. As summarized in Table 7, the reviewed studies identify three key benefit categories: data security and privacy, cost reduction, and trust and transparency. Each benefit is discussed in comparison with AI and Big Data to highlight blockchain's distinctive advantages in educational record and credential management.

A formal meta-analysis was not feasible due to the significant heterogeneity in study designs, blockchain platforms employed, institutional contexts, and outcome measures across the 64 included studies. This represents a limitation of the current review and reflects the early-stage nature of the field. As the literature matures and produces more methodologically homogeneous studies, future reviews should pursue quantitative synthesis. In the interim, we have introduced a structured evidence summary (Table 5), which categorizes studies by methodology type, application domain, and evidence strength as a partial remedy.

4.3 | What Challenges Are Associated With the Adoption of Blockchain in Education?

This research question explains the challenges related with blockchain adoption in education. As explained in Table 8, six key challenge categories were identified across the conducted studies: immutability, poor usability, data privacy and security, scalability, lack of adequate skills, and integration costs. Potential remedies proposed by researchers are discussed for each challenge.

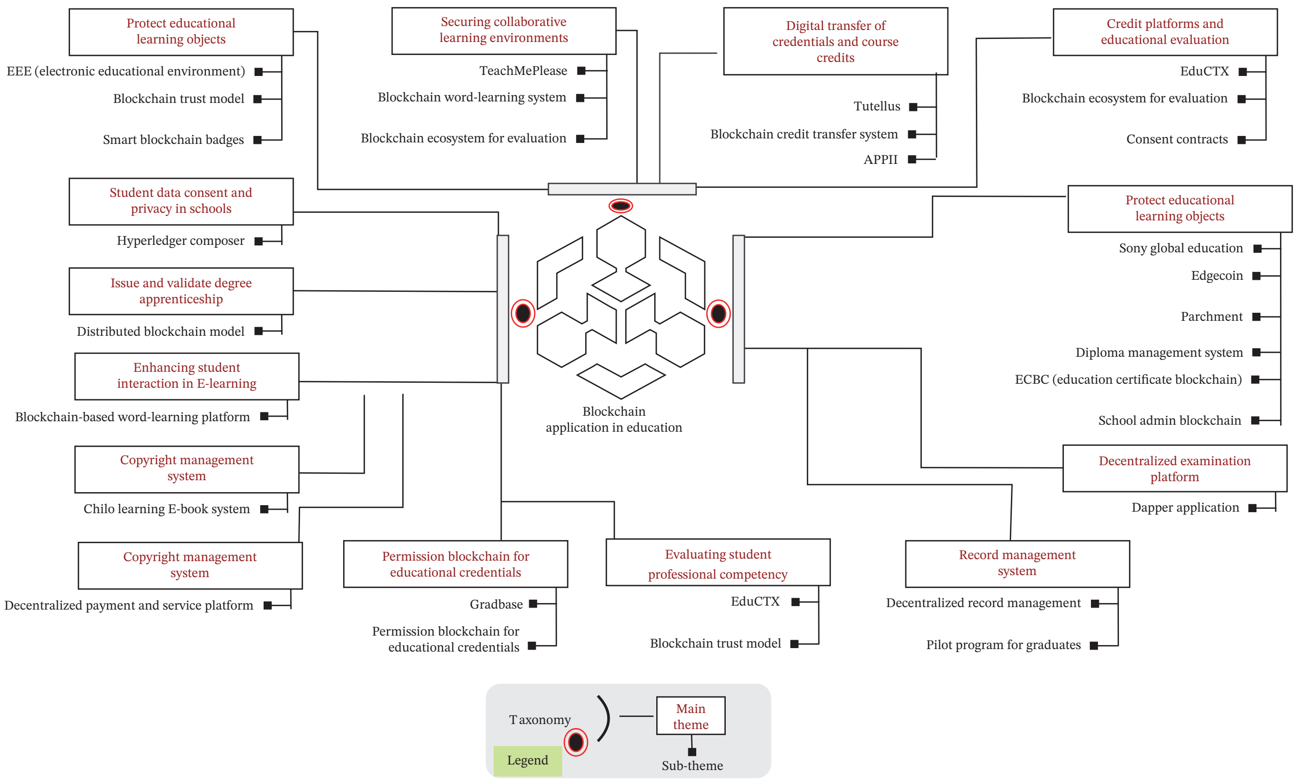

FIGURE 7 | Summary of key blockchain applications in education with practical examples. A formal three-dimensional taxonomy of these applications is presented in Section 4.6.

TABLE 7 | Blockchain benefits in education compared to other emerging technologies.

Benefits	Explanations	Cross-study insight
Data security and privacy	Blockchain data security and privacy Blockchain technology offers distinct advantages in the education sector, especially when compared to other emerging technologies such as artificial intelligence (AI) and Big Data Blockchain secures data transfers via cryptographic signatures, hashes, and a decentralized ledger, making it difficult for unauthorized parties to modify or access data. Bdiwi et al. [22] show that cryptographic signatures and hashes enhance transaction reliability and ensure tamper-proof data storage. Farah et al. [27] further demonstrate how blockchain supports tamper-evident learning trace repositories through distributed encryption mechanisms Comparison Artificial intelligence plays an important role in detecting cybersecurity risks in educational environments by identifying network irregularities. AI-based models automatically detect anomalous activities with high precision [56]. In contrast, Big Data systems, widely used in educational cloud services, introduce privacy risks due to centralized storage and insufficient transparency, potentially leading to data breaches and unauthorized access	The two studies directly addressing data security converge on cryptographic signatures and decentralized storage as the primary security mechanisms. However, neither study provides a formal security audit or comparative evaluation against established cybersecurity benchmarks. The evidence base for blockchain's security superiority over AI-based anomaly detection in educational contexts remains largely theoretical

(Continues)

TABLE 7 | (Continued)

Benefits	Explanations	Cross-study insight
Cost reduction	Blockchain technology reduces administrative and verification costs by storing records on decentralized platforms and eliminating intermediaries Compared to traditional systems, decentralized public and private blockchain networks offer cost-effective, location-independent access to records [23]. Blockchain further reduces credential verification expenses by automating validation processes [18] Comparison While cloud-based solutions offer centralized cost efficiencies, they often require third-party verification services that increase operational expenses. Blockchain, by contrast, provides a self-sustaining verification infrastructure, reducing dependency on external providers and lowering long-term costs	Both studies addressing cost reduction focus on eliminating intermediaries as the primary cost-saving mechanism. However, neither study accounts for the high initial deployment and infrastructure costs of blockchain systems, which are identified as a significant barrier in the challenges literature. Future research should conduct total cost of ownership analyses that balance deployment costs against verification savings
Trust and transparency	Blockchain enhances trust by enabling stakeholders to verify educational records without reliance on a central authority, ensuring tamper-proof and auditable data. For example, the EduCTX platform uses blockchain tokens to represent academic credits, offering a reliable and transparent grading and credentialing system for higher education institutions [63] Comparison Artificial intelligence improves transparency in adaptive learning systems by personalizing instruction and identifying learner needs. Chaudhry et al. [57] propose a transparency index for AI in education; however, AI systems typically operate under centralized control, limiting independent verification. Big Data analytics provide valuable educational insights but raise concerns regarding privacy, anonymity, and regulatory compliance. Florea and Florea [58] highlight that Big Data-driven education systems lack blockchain's decentralized and tamper-resistant trust model	The studies addressing trust and transparency consistently identify immutability and decentralization as blockchain's core trust advantages over both AI and Big Data. However, the reviewed studies do not address the trust implications of smart contract vulnerabilities, which could undermine the immutability guarantee if contract logic is flawed. This represents an important gap that future research should address

TABLE 8 | Blockchain adoption challenges in education.

Challenges	Explanations	Cross-study insight
Data privacy and security challenges	Ensuring data privacy and security is a major concern when implementing blockchain in education. While blockchain's transparency enhances trust, it also creates challenges in protecting sensitive information such as student records. Encryption techniques and hash-based data storage have been proposed as potential solutions; however, guaranteeing privacy without sacrificing transparency remains an open challenge [41, 45]	The two studies addressing this challenge converge on the transparency-privacy tension as the central unresolved problem. However, neither study proposes a technically specific resolution. The emerging ZKP-based architectures discussed in Section 4.5 represent a promising but as yet unevaluated solution in educational contexts
Immutability challenges	Immutability ensures that student records cannot be altered once added to the blockchain, thereby enhancing data integrity. However, this characteristic poses challenges for educational institutions when legitimate updates such as correcting errors or modifying credentials are required. Developing mechanisms for controlled updates without undermining immutability remains unresolved [49]	This challenge is addressed by only one study, reflecting a gap in the literature. The tension between immutability and the need for legitimate record correction is a fundamental architectural challenge that none of the reviewed application studies adequately addresses. Future research should explore versioning mechanisms and amendment protocols that preserve audit trails while enabling controlled updates

(Continues)

TABLE 8 | (Continued)

Challenges	Explanations	Cross-study insight
Poor usability	Usability refers to the degree of ease with which software systems can be effectively used by end users. Poor usability is recognized as one of the most significant barriers to the adoption of new technologies [42]. Kosmarski [46] further identifies usability as a critical challenge to blockchain deployment in education, noting that blockchain-based applications often present complex interfaces that require substantial user training, thereby limiting widespread adoption	Poor usability is the most frequently discussed challenge across five studies, reflecting a consistent finding that technical complexity is the primary barrier to end-user adoption. Notably, this challenge is rarely addressed in the application studies reviewed in Section 4.1, which tend to focus on technical architecture rather than user experience. This disconnect between technical design and usability requirements represents a significant gap in the literature
Scalability challenges	Scalability represents a major limitation for blockchain adoption in education, particularly when handling large volumes of academic data such as student records, examination results, and certificate transactions. For instance, the Bitcoin blockchain processes only three to seven transactions per second, rendering it unsuitable for high-volume educational environments [41]	Scalability is identified as a critical challenge in two studies, and its severity is supported by the concentration of conference-paper-level evidence in the application literature, which suggests that most reviewed systems have not been tested at production scale. The Layer-2 solutions discussed in Section 4.5 offer a technically viable pathway that future research should empirically evaluate in educational deployment contexts
Lack of adequate skills	Effective implementation of blockchain in education requires skilled and trained professionals capable of managing decentralized systems and cryptographic infrastructures. Many educational institutions lack the necessary expertise and financial resources to develop, deploy, and maintain blockchain-based solutions [44]	This challenge is addressed by one study, which identifies skills gaps as a systemic institutional barrier rather than an individual competency issue. Notably, none of the application studies reviewed in Section 4.1 address how institutions without specialist blockchain expertise could realistically implement the proposed systems, representing a significant gap between the technical proposals and their practical deployability
Cost challenges in integrating blockchain in education	The high initial cost of integrating blockchain into existing educational infrastructures, along with ongoing maintenance expenses, constitutes a significant barrier to adoption. As the number of users and data blocks increases, processing and storage costs rise substantially, making blockchain integration particularly challenging for smaller educational institutions [41]	Cost challenges are addressed by one study, which focuses on infrastructure and maintenance costs. This challenge is particularly significant when considered alongside the cost reduction benefits identified in Section 4.2, suggesting that blockchain's cost advantages are primarily realized at scale and in the long term, while initial deployment costs may be prohibitive for smaller institutions. Future research should develop cost–benefit frameworks tailored to different institutional sizes and resource contexts

4.4 | Software Engineering Implications

The results obtained in this review have some significant impacts on software engineers and system architects in the design of blockchain education platforms. First, the system architecture and applications reviewed indicate that there is a recurring need for a dual layer system where credential verification is public facing, and private student data management is carried out in a private layer. For example, the TeachMePlease platform is an Ethereum public layer and private layer. This separation of concerns should be used as a standard architectural pattern [66] of educational blockchain systems for engineers.

Second, from a smart contract design perspective, several reviewed applications feature implementations of smart contracts that facilitate automated credential issuance, consent management and the processing of payments. Smart contract auditability and formal verification of smart contracts must be a top priority for engineers because the errors in the logic of smart contracts cannot be corrected once they are deployed. Security of contracts is recommended to be implemented using frameworks like OpenZeppelin.

Third, regarding interoperability, the reviewed systems largely operate in institutional silos. Future systems should be designed around open standards such as the W3C verifiable credentials specification and decentralized identifier (DID) frameworks to enable cross-institutional credential portability.

Fourth, regarding privacy by design, the tension between blockchain transparency and student data privacy identified across multiple reviewed studies suggests that privacy-preserving architectures should be treated as a first-class design requirement rather than a post hoc consideration. Zero-knowledge proof (ZKP) implementations offer a technically promising pathway that engineers should evaluate during the design phase.

4.5 | Benchmarking Against Modern Blockchain Architectures

The majority of studies reviewed in this paper were conducted on first-generation blockchain platforms such as Ethereum and Hyperledger fabric. Since the publication of many of these studies, significant architectural advances have emerged that directly address the limitations identified in our review.

Layer-2 solutions: The scalability challenge, identified as a major barrier in Section 4.3, is directly addressed by Layer-2 protocols such as the lightning network and Ethereum's optimistic rollups. These solutions process transactions off-chain while maintaining on-chain security guarantees, potentially increasing throughput from the 3–7 transactions per second of base-layer Bitcoin to thousands of transactions per second. Educational record systems with high transaction volumes, such as large-scale examination platforms, should evaluate Layer-2 architectures as a primary design option.

ZKPs: The data privacy challenge identified across multiple reviewed studies can be substantially addressed by ZKP frameworks such as zk-SNARKs. These cryptographic protocols allow a party to prove knowledge of a credential without revealing the credential's contents, directly resolving the transparency-privacy tension that currently represents one of the most significant unsolved problems in blockchain-based education.

DID frameworks: The W3C DID standard provides a globally interoperable framework for self-sovereign identity that is directly applicable to the credential management and digital transfer applications reviewed in this study. Unlike the proprietary credential systems reviewed (e.g., APPII and Gradbase), DID-based systems would enable students to carry verifiable credentials across institutions and national borders without dependence on any single platform.

Table 9 provides a structured comparison of these modern architectures alongside blockchain, AI, and Big Data across key dimensions relevant to educational record and credential management systems.

4.6 | Formal Taxonomy and Theoretical Grounding

In order to overcome the descriptive character of the previous blockchain-education reviews, the current study suggests a formal three-dimensional taxonomic framework based on the principles of the systems theory and software architecture. The taxonomy divides blockchain applications in education into three orthogonal dimensions:

Dimension 1 (functional layer): Credentialing layer (issue certificates, verify, and revoke), transaction layer (credit transfer, payment processing, and smart contract execution), consensus layer (institutional validation, peer validation, or hybrid), and storage layer (on-chain vs. off-chain credential storage).

Dimension 2 (architectural pattern): (i) Institutional systems based on Hyperledger fabric with centralized permissioned, (ii) systems based on Ethereum with decentralized permissionless, and (iii) hybrid dual-layer (public for transparency and private for sensitive data) as in the case of the TeachMePlease architecture discussed in Section 4.1.

Dimension 3 (trust model): (i) Institution-based trust (credentials authenticated through issuing institutions), (ii) peer-based trust (consensus-based authentication among multiple parties), and (iii) self-sovereign trust (credentials owned by learners through DIDs).

Formally, let an educational blockchain system S be defined as a tuple:

$$S = \langle F, A, T, R, C \rangle,$$

where F is the functional layer credentialing, transaction, consensus, storage. A is the architectural pattern permissioned, permissionless, hybrid. T is the trust model institution-anchored, peer-anchored, self-sovereign. $R$is the set of blockchain records (credentials, transactions, and hashes). C is the set of smart contract functions automating educational processes. Each reviewed application from Table 6 is mapped to this taxonomic space. For example, Sony Global Education maps to $F = \{\text{Credentialing}\}$, $A = \text{Permissioned}$, and $T = \text{Institution-anchored}$, while EduCTX maps to $F = \{\text{Credentialing, Transaction}\}$, $A = \text{Permissionless}$, and $T = \text{Peer-anchored}$. This formal taxonomy provides theoretical grounding that is absent in prior descriptive reviews and enables a systematic comparison of blockchain architectures across educational contexts.

Theoretical motivation is based on the systems theory [67], in which educational blockchain is treated as an open system whose inputs (student records and credentials), processes (consensus and validation), outputs (verified credentials), and feedback mechanism (audit trails). Also, the taxonomy is informed by the actor-network theory [68], which acknowledges the role of human actors (students, administrators, and employers) and non-human actors (smart contracts, consensus algorithms, and hashes) as being equally important in defining the nature of blockchain-enabled educational networks.

This three dimensional taxonomic structure is visualized in Figure 8. Figure 8 portrays the three orthogonal dimensions, namely, functional layer (L_f), architectural pattern (A_p) and trust model (T_m) that jointly characterize any educational blockchain system as $\varepsilon = \langle L_f, A_p, T_m, \text{Platform} \rangle$. The lower panel of Figure 8 gives specific examples of this formal model with specific real-world platforms considered in this paper, such as Sony Global Education, EduCTX, TeachMePlease, and ECBC.

5 | Comparison With Existing Literature

The use of blockchain in education has been a topic of interest in several literature reviews; this study adds new perspectives and builds on existing knowledge in many aspects. The difficulties for the adoption of blockchain in educational institutions, mainly within the scope of institutional resistance and technical limitations, as described by Duwadi [50]. But this

TABLE 9 | Comparative matrix of blockchain, AI, big data, and modern blockchain architectures for educational records and credentials.

Dimension	Blockchain	AI	Big data	Modern blockchain architectures (Layer-2, ZKP, DID)
Data security and privacy	Cryptography + consensus; tamper-resistant records	Detects anomalies/threats; lacks tamper-proof guarantees	Aggregates large-scale data; increased privacy exposure risk.	ZKPs enable credential verification without data disclosure; enhances privacy beyond base-layer blockchain
Cost reduction	Reduces verification cost by removing intermediaries (e.g., credential checks)	Typically increases operational cost (training, inference, monitoring)	Infrastructure- and pipeline-heavy; cost depends on scale and governance	Layer-2 reduces transaction fees significantly by processing off-chain; lowers operational costs at scale
Trust and transparency	Independently verifiable, immutable audit trail	Limited transparency (black-box models); explainability required	Requires access control and governance to support accountable use	DID frameworks provide self-sovereign, independently verifiable identity without platform dependence
Scalability	Limited throughput (3–7 TPS for Bitcoin); major barrier for large-scale educational deployments	Scales well with compute resources; not transaction-bound	Highly scalable with distributed infrastructure; governance complexity increases with scale	Layer-2 protocols increase throughput to thousands of TPS; directly addresses base-layer scalability limitations
Interoperability	Largely platform-specific; limited cross-institutional credential portability in reviewed systems	Model-agnostic; integrates across platforms with APIs	Platform-dependent; requires data pipeline alignment for integration	W3C DID and verifiable credentials standards enable cross-institutional and cross-border credential portability
Privacy by design	Transparency-privacy tension; on-chain data exposure risk for sensitive student records	Privacy depends on data governance and model design	Centralized storage increases privacy exposure; requires strong governance	ZKP-based architectures treat privacy as first-class design requirement; resolves transparency-privacy tension
Illustrative examples	EdgeCoin; Sony Global Education (records protection); EduCTX (credit platform)	Security analytics/adaptive learning (context-dependent)	Learning analytics platforms (privacy-preserving aggregation needed)	Lightning network (scalability); zk-SNARKs (privacy-preserving credentials); W3C DID (self-sovereign identity)

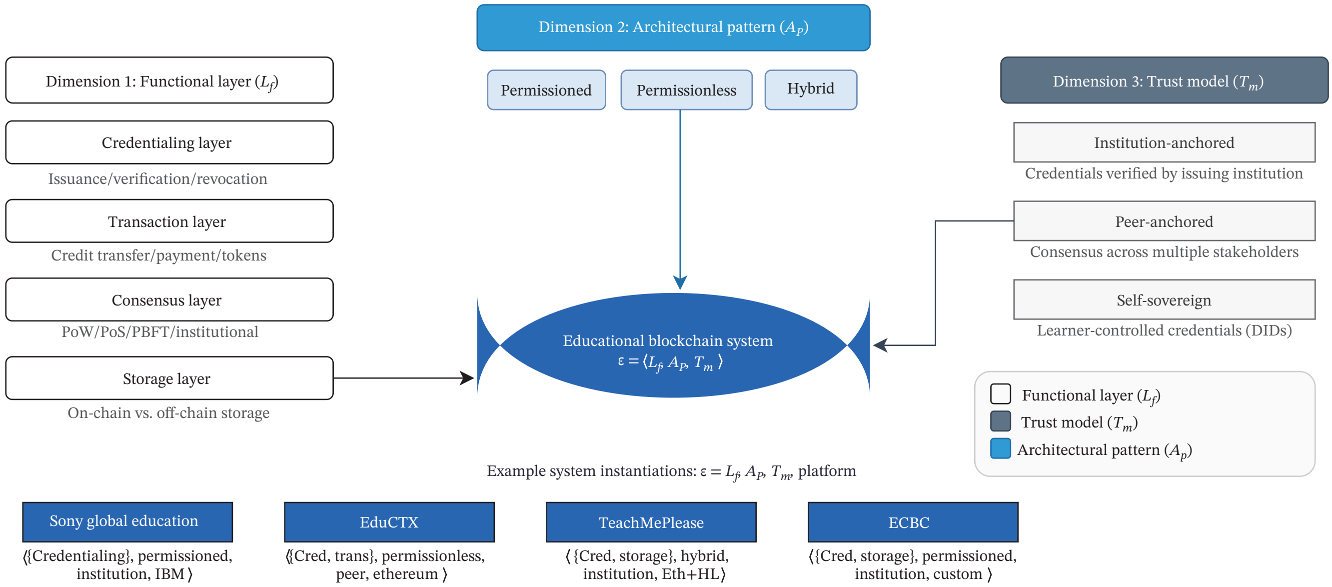

FIGURE 8 | Formal three-dimensional taxonomic framework for blockchain-enabled education systems.

study only covered research published prior to 2021 and was mostly focused on the problems rather than solutions or implementation tips. The present review, however, covers a wider time period (2017–2025) and provides a more extensive review of adoption challenges and practices in the use of blockchain in education. Although the focus of Duwadi [50] was on barriers, this review also highlights the tangible benefits and real-world applications of blockchain technology, including Sony Global Education and Parchment certificate management system.

The works of Liu et al. [32] and Mikroyannidis et al. [34] have explored the application of blockchain to enhance the student assessment system and facilitate lifelong learning systems. These studies, however, focused mainly on technical architectures and high level use cases, and provided little guidance on how to integrate blockchain into the educational workflow. This review on the other hand offers specific suggestions for implementation such as pilot programmes for certificate management and decentralized platforms for examination. This review offers a more comprehensive and action-oriented understanding of the potential for blockchain to revolutionize the education sector by exploring a range of blockchain applications and highlighting the practical strategies for implementing them.

While the previous reviews listed the applications that have been built on blockchain, this review also explicitly links each application to a structured deployment approach that is based on documented real-world cases. For example, the management of certificates is based on Sony Global Education and Parchment, and the credit transfer is based on the operational model of the EduCTX platform. Each strategy outlines a phase of action, scope for a small-scale pilot, and measurable benefits, giving a degree of implementation specificity that is not found in previous reviews. Besides, the contributions in the taxonomy of this application, namely decentralized examination platform, student data consent management, and copyright protection of learning objects in education were not fully covered in previous studies such as [49, 50].

Our review is broader in terms of educational coverage compared to the recent studies, which concentrate on particular areas of technical domains. Shah and Raj [62] focus on public–private partnerships of CBDCs rather than educational governance. Hapuarachchi et al. [59] focus on cybersecurity training infrastructure while we discuss pedagogical and administrative uses. This study [60] suggests one Hyperledger-ML architecture, and we compare various platforms (Ethernet, Hyperledger, and permissioned/public) using selected studies. Alwakid and Dahri [61] apply quantitative SEM analysis to gamification, but our qualitative mapping shows a broader taxonomy of applications, benefits, and challenges in the education sector as a whole.

5.1 | Open Research Issues

Based on selected studies in this systematic review, it presents benefits and adoption issues in education, there are still multiple gaps in research that need to be addressed. The open research issues outlined below are used to direct future academic research.

5.1.1 | Scalability of Blockchain Solutions in Large Scale Educational Deployments

The majority of the reviewed studies describe pilot applications or small scale prototypes. None of the studies included have offered longitudinal data of blockchain performance on an institutional or cross institutional basis with thousands of students. The next step in the research should be to empirically test blockchain at the production level of educational load.

5.1.2 | High Transactions Costs and Energy Usage

Although blockchain has the benefit of reducing costs due to the absence of intermediaries, its operational costs in terms of transaction fees and energy intensive consensus mechanisms have not been adequately studied [69–71]. Open research involves comparative cost–benefit analysis of various consensus algorithms to institutions with small IT budgets.

5.1.3 | Privateness vs. Publicity Implementation

The literature reviewed indicates variance in understanding which type of blockchain, permissioned or permissionless, suits education better. Future studies ought to come up with decision models that guide institutions to choose the right architecture in respect to use case, data sensitivity and governance.

5.1.4 | Student Data Privacy (Mechanisms)

The conflict between blockchain transparency and privacy of student data is still unsettled. Open research incorporates the design and validation of ZKP applications to support education credential checks that meet GDPR and FERPA.

5.1.5 | Interoperability Standards for Institutional Credential Portability

The majority of blockchain-based credential systems exist in institutional silos. Open research involves W3C DID and verifiable credentials frameworks development and testing in several universities.

5.1.6 | Human-Centered Design and Usability

The most commonly argued adoption issue is poor usability, but there is no study that systematically examines user experience. Further studies need to be done on the aspects of intuitive interface and recovery of the private key by nontechnical users.

5.1.7 | Smart Contract Auditability

Formal verification of educational smart contracts and the legal enforceability of blockchain-based credentials in existing regulatory frameworks are open research problems.

5.2 | Strengthening the Conceptual Foundations of Blockchain and Decentralization

Although the importance and need to use blockchain in education are discussed in this section, recent interdisciplinary research builds upon the conceptual framework of decentralization, immutability, and distributed governance. Blockchain can enable a secure decentralized communication network between distributed IoT devices [71, 72], without depending on any central authority, and add cryptographic verification mechanisms [69]. All of these studies demonstrate the theoretical basis for the idea that a decentralized blockchain is an appropriate approach to target education systems that have a broad level of trust, verification and secure records management. New technologies, including cryptographic security, have been created to improve the prospects of educational ecosystems powered by blockchain technology. Research on new cryptographic approaches for Industry 5.0 is presented in [73] and the importance of privacy preserving infrastructures, secure communications, and resilient decentralized systems is stressed. The relevance of these findings is significant when considering the educational ecosystem, where blockchain-based educational platforms need to guarantee the integrity of academic qualifications, students' records, and electronic learning assets, among other considerations. Blockchain architectures offer higher assurances of distributed trust management, immutability, and transparency when compared with traditional centralized systems.

5.3 | Educational Context, ICT Adoption, and Institutional Transformation

The lack of educational theory and institutional adoption perspectives integration, is one of the major criticisms of blockchain research in education. The lack of contextual understanding of the practical barriers for blockchain adoption in educational institutions has been mitigated by the studies on ICT adoption and digital learning transformation. Some of the most important influences on technology adoption in higher education are: infrastructure readiness; institutional support; digital literacy; perceived usefulness; and organizational resistance [74]. Shaikh and Khoja [75] highlight that digital transformation in Universities must rely on technological systems, but also on the readiness of professors, the support of policies, the governance models, and the culture of the institutions. The skills gaps, integration costs, usability problems, and institutional resistance that are all discussed in this review are directly reflected in these findings. Although blockchain offers secure and decentralized infrastructure for education records and credentials, their successful implementation relies heavily on the institutional readiness and receptivity of the users. Thus, blockchain is not only a technical change, but a change process in the organization and pedagogy.

Learner-centered education models are already contributing to the support for decentralized education systems powered by blockchain. In modern education, two of the main points to keep in mind are learner autonomy, personalized learning paths and the decentralization of education resources, which are among the points highlighted [76, 77]. These views are very similar to the ones that are advocated for blockchain based education ecosystems in which students are empowered to take control of their credentials, learning paths, skills, and micro certifications, without being completely reliant on centralized institutional repositories. Blockchain can be beneficial in the personal learning environments' extension, enabling the self learning records and the authentication of competency transparency, as well as secure, lifelong learning portfolios. Recent studies on the educational architecture in today's world validate the linkage between central and decentral structures. The digital educational infrastructures are meant to enable flexible and scalable learning environments [78]. As reported in [79], the dependence on the smart educational technologies for the enhancement of collaboration, assessment, and academic management is increasing. The findings are also quite relevant for blockchain technology in education since decentralized blockchain architectures have similar objectives of distributing control, minimizing central bottlenecks and enhancing secure collaboration between various educational actors. Blockchain can offer advantages to education ecosystems in terms of transparency, ownership, interoperability, and trust over traditional centralized education ecosystems. However, literature reviewed also indicates a need to take into account a balance of decentralization and institutional governance, usability, readiness of infrastructure, and the alignment of education policies.

5.4 | Data Management, Security, Privacy, and Trust Mechanisms

There is need for security and trust management systems, and tamper proof record management systems in blockchains for education. Recent interdisciplinary research on blockchain, cryptographic security, and decentralized infrastructures are of particular interest as they provide significant technical understandings that are relevant to education oriented systems. The distributed IoT environment is used to illustrate and show the use of blockchain-based architectures for providing secure communication, decentralized verification, and tamper resistant infrastructures [72, 80]. From the security standpoint, it emphasizes the need for cryptographic security, privacy enhancing architectures, and secure decentralized infrastructures [73]. This research provides valuable insights into the importance of integrating blockchain with advanced cryptographic techniques to prevent privacy erosion, unauthorized access, and cyber threats in the educational sector. The underscore highlights the significance of blockchain in developing trustworthy systems for secure data management and automation [81], thus enhancing the feasibility of blockchain's role in credential verification and decentralized educational governance.

6 | Conclusion

This systematic review aims to investigate the use of blockchain in the education sector, focusing on its advantages and associated challenges. The review is structured around three key areas: (1) potential applications of blockchain in education, (2) its benefits, and (3) adoption challenges. This framework guides the analysis toward achieving the research objective. The comprehensive analysis sheds light on how blockchain can be effectively utilized in educational contexts. In this review article, the author provides a clear and lucid explanation of the findings. Among the various applications identified, student competence assessment in professional fields has attracted considerable research interest. Another significant application is certificate management systems, which institutions have widely adopted for their efficiency. To illustrate blockchain applications in practice, this review highlights the Sony Global Education application—a repository that stores student records and allows over 150,000 users worldwide to log in and solve mathematical problems. This study concentrates on academic articles and conferences but neglects industry reports. The addition of industry reports and practitioner views may provide a more holistic capturing and inclusion of practical information regarding the uses of blockchain in education. Further, the included conference papers have undergone the same five-criterion quality screening as journal articles, but it is acknowledged that in rapidly changing technical fields like blockchain, conference papers often are at the cutting edge of research and publication before journal papers. All included studies met the defined quality threshold irrespective of their publication venue, and the evidence strength ratings presented in Table 5 provide a transparent and study level account of the quality of the evidence base across all 64 included studies.

7 | Future Work

In future research, we will focus on developing deeper into the scalability of blockchain solutions in education; specifically, our focus is on exploring how blockchain technology can handle the large-scale implementations of learners and institutions. We will further focus on high transaction costs and energy consumption associated with blockchain technology and compare private and public blockchain implementation in the education sector.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available upon request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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