

Future-Ready Auditors The Impact of AI Competency on Sustainability Assurance Quality in Emerging Markets

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Abstract

Objective: This study aims to examine the development of academic literature on artificial intelligence (AI) competency, sustainability assurance quality, and the role of future-ready auditors in addressing the challenges of ESG governance and digital transformation in emerging markets.

Design/Methods/Approach: This study employs a Systematic Literature Review (SLR) approach using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Data were collected from the Scopus database using predefined keywords related to artificial intelligence, auditing, sustainability assurance, ESG reporting, and digital governance. Articles published between 2021 and 2026 were screened through inclusion and exclusion criteria, resulting in 19 relevant studies for analysis. Bibliometric analysis and thematic synthesis were conducted to identify research trends, key themes, and knowledge gaps.

Findings: The findings reveal that AI, blockchain, big data analytics, and Industry 4.0 technologies have significantly transformed sustainability assurance by improving auditability, transparency, accountability, predictive risk assessment, continuous auditing, and automated verification processes. AI competency emerges as a critical capability for auditors to enhance sustainability assurance quality through effective ESG monitoring and digital assurance practices. However, emerging markets continue to face challenges related to limited digital infrastructure, low institutional readiness, governance capability gaps, and insufficient AI literacy among auditors.

Originality/Value: This study contributes to the existing literature by integrating discussions on AI competency, sustainability assurance quality, and future-ready auditors within the context of emerging markets. Unlike prior studies that primarily focus on technological systems and digital governance, this review highlights the strategic role of auditor AI competency as a key determinant of sustainability assurance effectiveness.

Practical/Policy implication: The findings suggest that organizations, audit firms, and professional bodies should strengthen AI literacy, digital capability, and sustainability-oriented assurance skills among auditors. Policymakers and regulators are encouraged to develop supportive digital governance frameworks, AI-related auditing standards, and capacity-building programs to enhance the effectiveness of sustainability assurance and ESG reporting in emerging economies.

Keywords: *ESG governance; Digital Assurance Ecosystem; Blockchain Technology; Audit Quality; Industry 4.0*

JEL Classification: M42, M48 [author should add 1-3 JEL classification number, information guide for the Journal of Economics Literature (JEL) can be found at <https://www.aeaweb.org/jel/guide/jel.php>]

1. INTRODUCTION

The rapid advancement of digital transformation in recent years has brought significant changes to business practices, organizational governance, and modern assurance systems. Technological developments such as artificial intelligence (AI), blockchain, big data analytics, cloud systems, and Industry 4.0 have encouraged organizations to develop data management and sustainability governance systems that are more transparent, accountable, and technology-driven (Kroon et al. 2021; Moll and Yigitbasioglu 2019; Sutton et al. 2023). These transformations have also been driven by increasing global demands for sustainability

reporting, environmental, social, and governance (ESG) performance, and organizational accountability in addressing sustainable development challenges (Velte 2024). In this context, the auditing profession has undergone substantial transformation, as auditors are no longer focused solely on traditional financial assurance but are increasingly involved in sustainability assurance, ESG verification, and digital governance systems that require more sophisticated technological capabilities (Appelbaum et al. 2023; Kokina and Davenport 2017).

The growing attention to sustainability assurance has emerged alongside increasing stakeholder awareness regarding the importance of transparency and accountability in organizational sustainability reporting. Organizations are currently expected not only to provide reliable financial statements but also to ensure the credibility of sustainability reporting and ESG disclosures through trustworthy assurance systems (O'Dwyer et al., 2022; Velte and Stawinoga 2023). Consequently, sustainability assurance has become a strategic issue in modern auditing practices, particularly due to the rising risks of greenwashing, ESG data manipulation, and inaccuracies in sustainability reporting across various industries (Christensen et al., 2022; Michelon et al., 2021). To address these challenges, organizations have increasingly adopted AI, blockchain, and digital monitoring systems to enhance traceability, auditability, and assurance quality regarding their sustainability performance (Dai and Vasarhelyi 2017; Lombardi et al. 2021).

Consistent with these developments, previous studies have demonstrated that artificial intelligence plays a crucial role in improving the effectiveness of auditing and governance systems. AI has been widely applied in automated auditing, anomaly detection, predictive risk assessment, fraud detection, continuous auditing, and ESG monitoring to support faster and more accurate data-driven decision-making processes (Issa et al., 2016; Kroon et al., 2021; Sutton et al., 2023). Furthermore, blockchain technology and smart contracts have increasingly been utilized to create immutable audit trails, improve reporting transparency, and strengthen compliance systems within sustainability governance frameworks (Dai and Vasarhelyi 2017; Rozario and Thomas 2019). These transformations indicate that the quality of modern assurance is becoming increasingly dependent on the ability of organizations and auditors to effectively leverage digital technologies.

On the other hand, the development of the digital assurance ecosystem requires auditors to possess new competencies that are adaptable to technological advancements. Future-ready auditors are expected to have not only conventional accounting and auditing expertise but also AI competency, digital capabilities, data analytics skills, and a comprehensive understanding of governance technologies and ESG systems (Bakarich and O'Brien 2021; Teeter et al., 2024). Several studies have emphasized that AI competency among auditors is a critical factor in enhancing audit quality, transparency, accountability, and the effectiveness of sustainability assurance in the era of digital transformation (Kokina and Blanchette 2019; Sutton et al., 2023). Moreover, the implementation of AI in auditing is influenced by institutional readiness, governance capability, regulatory compliance, and technology adoption levels that vary across countries and organizations (Alkaraan et al. 2023; Moll and Yigitbasioglu 2019).

Despite these opportunities, the implementation of artificial intelligence in sustainability assurance continues to face significant challenges, particularly within emerging markets. Developing countries generally experience limitations in digital infrastructure, AI readiness, governance systems, and human resource quality necessary to support digital auditing transformation (Alfityani et al. 2024; Dal Mas et al. 2026). These conditions result in

sustainability assurance quality that remains suboptimal despite the increasing demand for ESG reporting and sustainability governance practices (Velte 2024). Furthermore, the lack of standardized sustainability assurance frameworks and limited digital competencies among auditors create challenges in establishing consistent transparency and reliability in sustainability reporting processes (Sawaya et al. 2026).

A substantial body of prior research has examined artificial intelligence, blockchain, ESG reporting, digital governance, and sustainability systems within the context of auditing and modern organizations (Appelbaum et al. 2023; Lombardi et al. 2021; Velte 2024). However, most studies have primarily focused on technological aspects and digital system development, while research specifically examining the relationship between auditor AI competency and sustainability assurance quality remains relatively limited (Bakarich and O'Brien 2021; Teeter et al., 2024). In addition, previous studies have largely been conducted in developed economies and organizations with high levels of digital maturity, leaving the context of emerging markets underexplored within the literature on digital assurance and sustainability governance. This situation highlights an important research gap that warrants further investigation.

Based on these circumstances, this study offers novelty by integrating the perspectives of auditor AI competency, sustainability assurance quality, and emerging markets within a comprehensive analytical framework. The study not only discusses artificial intelligence as a supporting technology for auditing but also positions auditor competency as a central factor in enhancing sustainability assurance quality in the digital era. Furthermore, this research contributes to the growing literature on future-ready auditors by emphasizing the importance of digital capability, AI literacy, governance understanding, and ESG assurance competence in responding to digital auditing transformation and sustainability governance challenges in developing economies (Alkaraan et al. 2023; Bakarich and O'Brien 2021). Based on the preceding discussion, this study is designed to address the following research questions:

RQ1: How has research on artificial intelligence and sustainability assurance evolved within the academic literature?

RQ2: What is the role of auditor AI competency in improving sustainability assurance quality during the era of digital transformation?

RQ3: What factors influence the effectiveness of artificial intelligence-based sustainability assurance in emerging markets?

RQ4: What are the future development directions of future-ready auditors in addressing the challenges of ESG governance, digital transformation, and sustainability reporting?

Accordingly, this study aims to analyze the development of literature related to artificial intelligence, auditing, and sustainability assurance, identify existing research gaps within the context of emerging markets, and develop a conceptual understanding of the importance of auditor AI competency in supporting the enhancement of sustainability assurance quality in the digital era.

2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

2.1 Artificial Intelligence (AI) Competency

Artificial intelligence (AI) competency refers to an individual's ability to understand, operate, analyze, and utilize AI-based technologies to support decision-making processes and

organizational activities effectively. In the context of modern auditing, AI competency encompasses not only technical expertise related to machine learning, big data analytics, automation systems, and blockchain technologies but also auditors' capabilities in understanding digital governance, ESG systems, and technology-driven data interpretation (Issa et al., 2016; Kokina and Davenport 2017; Sutton et al., 2023). The rapid advancement of digital transformation has significantly altered the auditing profession, shifting from traditional audit approaches toward technology-enabled assurance systems characterized by data-driven processes, automation, and continuous monitoring (Appelbaum et al. 2023; Moll and Yigitbasioglu 2019).

Previous studies have demonstrated that AI competency plays a critical role in improving auditing effectiveness and modern assurance quality. The application of artificial intelligence enables auditors to conduct anomaly detection, fraud detection, predictive risk assessment, and automated verification with greater efficiency and accuracy compared to conventional audit methods (Issa et al., 2016; Kokina and Blanchette 2019). Furthermore, the integration of AI into auditing processes contributes to enhanced transparency, accountability, and auditability in sustainability reporting and ESG assurance systems (Alkaraan et al. 2023; Velte and Stawinoga 2023). Consequently, future-ready auditors are expected to possess adequate digital literacy and AI capabilities to adapt to technological advancements and the growing complexity of modern governance environments (Bakarich and O'Brien 2021; Teeter, Alles, and Vasarhelyi 2024).

Despite its potential benefits, the implementation of AI competency within the auditing profession continues to face substantial challenges, particularly in emerging markets. Limitations in digital infrastructure, low levels of technological readiness, and inadequate technological competencies among auditors hinder the effective adoption of AI in sustainability assurance practices across many developing economies (Alfityani et al. 2024; Dal Mas et al. 2026). Moreover, issues related to ethical governance, regulatory compliance, algorithmic transparency, and trust in AI systems represent critical challenges in technology-based auditing and sustainability assurance implementation (Alkaraan et al. 2023; Sutton et al., 2023). Therefore, AI competency has become a strategic determinant of auditors' readiness to operate effectively in the era of digital transformation and ESG-oriented governance.

2.2 Sustainability Assurance Quality

Sustainability assurance quality refers to the extent to which assurance processes ensure the reliability, transparency, and credibility of sustainability reporting and ESG disclosures. Sustainability assurance aims to enhance stakeholder confidence in non-financial information disclosed by organizations regarding their environmental, social, and governance performance (O'Dwyer et al., 2022; Velte 2024). In recent years, sustainability assurance has emerged as a critical component of corporate governance due to increasing demands for accountability, transparency, and sustainable business practices across industries (Velte 2024).

Technological advancements such as artificial intelligence, blockchain, cloud computing, and big data analytics have significantly transformed sustainability assurance systems. These technologies facilitate continuous monitoring, real-time verification, automated compliance assessment, and digital traceability, thereby improving assurance effectiveness and efficiency (Appelbaum et al. 2023; Dai and Vasarhelyi 2017). Furthermore, blockchain technology and smart contracts have increasingly been adopted to create immutable audit trails

and enhance transparency in sustainability reporting, reducing the risks of ESG data manipulation and greenwashing practices (Lombardi et al. 2021; Rozario and Thomas 2019). As a result, sustainability assurance quality is no longer determined solely by traditional assurance standards but also by the ability of organizations and auditors to integrate digital technologies into modern assurance processes (Velte 2024).

Nevertheless, sustainability assurance quality continues to face significant challenges, particularly in emerging markets characterized by varying levels of institutional readiness and governance maturity. Many organizations in developing countries experience difficulties in implementing ESG governance frameworks, digital monitoring systems, and standardized assurance procedures, limiting the effectiveness of sustainability assurance practices (Alfityani et al. 2024; Sawaya et al. 2026). In addition, insufficient digital competencies among auditors and the absence of comprehensive sustainability assurance regulations contribute to inconsistencies in reporting transparency and reliability (Velte 2024). Therefore, strengthening auditors' AI competency is considered an important factor in enhancing sustainability assurance quality in the digital era.

2.3 Digital Governance and ESG Reporting

Digital governance refers to organizational governance systems that leverage digital technologies to support transparency, accountability, risk management, and effective decision-making processes. Within the context of sustainability governance, digital governance plays a vital role in ensuring that sustainability reporting and ESG disclosures are conducted in a transparent, credible, and accountable manner (Alkaraan et al. 2023; Moll and Yigitbasioglu 2019). Emerging technologies such as artificial intelligence, blockchain, big data analytics, and cloud computing have accelerated the transformation of governance systems toward more integrated, data-driven, and real-time monitoring approaches (Kroon, Alves, and Martins 2021)(Sutton et al., 2023).

ESG reporting has become a fundamental instrument of modern sustainability governance because it provides stakeholders with information regarding organizational performance beyond traditional financial indicators, including environmental and social responsibility dimensions (Velte and Stawinoga 2023). Effective ESG reporting requires high-quality assurance systems to ensure the credibility of information provided to investors, regulators, and other stakeholders (O'Dwyer et al., 2022). Prior studies indicate that artificial intelligence and blockchain technologies enhance transparency, traceability, and auditability in ESG reporting through automated verification systems and predictive analytics capabilities (Appelbaum et al. 2023; Lombardi et al. 2021). These findings demonstrate the close relationship between digital governance, ESG reporting, and the ongoing transformation of sustainability assurance practices.

However, the implementation of digital governance and ESG reporting continues to encounter challenges, particularly in emerging markets with varying levels of digital maturity and governance capabilities. Many organizations face difficulties related to data integration, regulatory compliance, and the effective utilization of digital assurance systems to support sustainability reporting (Alfityani et al. 2024; Sawaya et al. 2026). Furthermore, increasing risks associated with cybersecurity threats, data manipulation, and greenwashing create new challenges for technology-based governance systems (Christensen et al., 2022; Velte 2024). Consequently, enhancing auditors' digital capabilities and AI competencies has become

increasingly important for supporting effective ESG governance and sustainability assurance systems.

2.4 Emerging Markets and Digital Auditing Transformation

Emerging markets are developing economies experiencing rapid economic growth, industrialization, and digital transformation. In recent years, these economies have faced increasing global pressure to improve sustainability governance, ESG disclosures, and reporting transparency as part of broader sustainable development agendas and global economic integration processes (Alfityani et al. 2024; Dal Mas et al. 2026). As a result, organizations and auditing professions in emerging markets have increasingly adopted artificial intelligence, blockchain technologies, cloud systems, and digital governance tools to improve auditing effectiveness and sustainability assurance quality (Alkaraan et al. 2023).

Digital auditing transformation in emerging markets is characterized by the growing adoption of AI-based auditing systems, automated monitoring technologies, data analytics tools, and digital assurance ecosystems in governance and sustainability reporting processes. These technologies enable auditors to perform risk assessments, anomaly detection, and continuous auditing more efficiently and accurately, thereby improving audit quality and sustainability assurance effectiveness (Appelbaum et al. 2023; Issa, Sun, and Vasarhelyi 2016). Furthermore, blockchain technology and smart contracts have increasingly been implemented to improve traceability and transparency within ESG reporting and organizational governance systems (Dai and Vasarhelyi 2017; Rozario and Thomas 2019). These developments suggest that digital transformation has become a critical factor in enhancing assurance quality and modern governance practices in developing economies.

Despite these advancements, emerging markets continue to face numerous obstacles in implementing AI-based digital auditing and sustainability assurance systems. Limitations in digital infrastructure, low institutional readiness, inadequate AI competencies among auditors, and differences in regulatory frameworks contribute to uneven digital auditing transformation across developing countries (Alfityani et al. 2024; Dal Mas et al. 2026). In addition, challenges associated with governance quality, cybersecurity risks, and technology adoption influence the effectiveness of sustainability assurance practices within emerging markets (Alkaraan et al. 2023; Velte 2024). Therefore, developing auditors' AI competencies and digital capabilities represents a strategic initiative to enhance the auditing profession's readiness to address evolving governance and sustainability assurance challenges in the digital transformation era.

3. METHODS

3.1 Data Source

The data source for this study was obtained from scientific articles indexed in the Scopus database, which served as the primary source for the systematic literature review (SLR) process ((Singh et al. 2021). Scopus was selected because it provides extensive coverage of reputable international journals and offers high-quality scholarly publications relevant to the topics of artificial intelligence (AI), auditing, sustainability assurance, ESG reporting, and digital governance. The article search process was conducted using several keyword combinations, including "artificial intelligence," "AI competency," "digital capability," "audit quality," "sustainability assurance," "ESG assurance," "sustainability reporting," and

“emerging markets,” within the title, abstract, and keyword fields. The review was limited to articles published between 2021 and 2026 to capture the most recent developments related to digital transformation in the auditing profession and sustainability assurance. Subsequently, the identified articles were screened using predetermined inclusion and exclusion criteria, resulting in 19 relevant studies that aligned with the research focus on the role of AI competency in enhancing sustainability assurance quality within the context of emerging markets.

3.2 Inclusion and Exclusion Criteria

The inclusion criteria were established to ensure that the selected articles possessed strong relevance to the topic of auditor Artificial Intelligence (AI) competency and sustainability assurance quality within emerging market contexts. The inclusion criteria comprised: (1) research articles discussing the use, competency, adoption, or capability of AI, digital technologies, data analytics, machine learning, or digital audit technologies in auditing and assurance practices; (2) articles examining sustainability assurance, ESG assurance, sustainability reporting, non-financial reporting, or sustainability auditing; (3) empirical and conceptual studies published in reputable international journals indexed in Scopus; (4) articles published between 2021 and 2026 to capture recent developments in digital auditing transformation and sustainability assurance; (5) studies conducted in developing countries or emerging markets, including regions such as ASEAN, Asia, Africa, the Middle East, and Latin America; and (6) articles published in English with accessible abstracts and full texts to facilitate comprehensive analysis.

Conversely, exclusion criteria were applied to filter out studies that were not sufficiently relevant to the research focus, thereby maintaining the quality and rigor of the systematic literature review. The exclusion criteria included: (1) articles discussing artificial intelligence in fields unrelated to auditing, assurance, accounting, or sustainability reporting; (2) studies focusing exclusively on traditional financial auditing without addressing sustainability assurance, ESG issues, or auditors’ digital competencies; (3) conference proceedings, editorial notes, book reviews, theses, working papers, and other non-peer-reviewed documents; (4) duplicate articles identified during the database search process; (5) studies lacking clear methodological descriptions and research findings; (6) articles published before 2021, which were considered less representative of recent developments in AI and sustainability assurance; and (7) studies whose research contexts were unrelated to emerging markets or did not address the transformation of auditor competencies in the digital era.

3.3 PICOS Framework

The study selection criteria in this systematic literature review were developed using the PICOS framework (Population, Intervention, Comparison, Outcome, and Study Design) to ensure that the article screening process was conducted systematically, rigorously, and consistently with the research objectives (Wang et al. 2022). The PICOS framework was employed to identify studies relevant to auditor AI competency, sustainability assurance quality, and the context of emerging markets. Through this approach, the screening process became more objective because each study was evaluated based on the suitability of the research population, the type of digital technology intervention examined, the outcomes reported, and the research design employed in previous studies. The use of the PICOS

framework also facilitated the development of a transparent and replicable review process, thereby enhancing the reliability and validity of the systematic literature review findings.

Table 1. PICOS Framework

PICOS	Inclusion Criteria	Exclusion Criteria
Population	Articles discussing auditors, accountants, assurance providers, business organizations, financial institutions, ESG professionals, or corporate governance within the context of digital transformation and sustainability assurance.	Articles focusing exclusively on consumers, education, tourism, agriculture, healthcare, or other sectors without relevance to auditing, assurance, or ESG governance.
Intervention	Articles examining artificial intelligence (AI), blockchain, big data analytics, cloud systems, Industry 4.0, Quality 4.0, digital governance, automation, or digital technologies supporting auditing and sustainability assurance.	Articles discussing general technologies without relevance to audit quality, ESG assurance, sustainability reporting, or digital assurance ecosystems.
Comparison	Articles comparing traditional auditing and digital auditing, conventional assurance and technology-enabled assurance, or discussing changes in auditor competencies resulting from digital transformation.	Articles that do not address technological change, competency development, or the impact of digital technologies on auditing and sustainability assurance.
Outcome	Articles reporting outcomes related to audit quality, sustainability assurance quality, ESG transparency, accountability, auditability, governance effectiveness, continuous auditing, or digital assurance capability.	Articles that do not discuss outcomes related to assurance quality, audit effectiveness, governance transparency, or sustainability accountability.
Study Design	Empirical studies, conceptual papers, systematic literature reviews, bibliometric studies, case studies, quantitative research, and qualitative research published in Scopus-indexed international journals between 2021 and 2026.	Conference proceedings, theses, editorial notes, book reviews, non-peer-reviewed papers, duplicate articles, and articles published before 2021.

Source: Developed by the authors based on the PICOS framework adapted from Wang *et al.* (2022).

3.4 Search Strategy

The search strategy in this study was conducted systematically using the Systematic Literature Review (SLR) approach to identify articles relevant to the topic of auditor AI competency and sustainability assurance quality in emerging markets. The literature search was performed using the Scopus database because it provides extensive coverage of reputable and multidisciplinary international journals, particularly in the fields of accounting, auditing, sustainability, and digital transformation. The search process began with the identification of key terms, the development of keyword combinations using Boolean operators (AND and OR), and the filtering of articles based on publication year, document type, language, and topic relevance. Subsequently, the retrieved articles underwent a multi-stage screening process based on titles, abstracts, keywords, and full-text reviews using the predetermined inclusion and exclusion criteria to ensure alignment with the research objectives. The keywords used in the search process included several combinations of terms such as: ((AI OR digital OR technolog) AND (audit* OR assurance) AND (sustainab* OR ESG)). These keyword combinations were applied to the title, abstract, and keyword fields using Boolean operators to broaden the scope of relevant article retrieval. Furthermore, the study limited the search to articles published between 2021 and 2026 to capture the most recent developments related to artificial intelligence and sustainability assurance within the auditing profession. All search and article collection procedures were conducted through the Scopus database, with the final search performed on 20 May 2026.

3.5 Search Results

The process of identifying and selecting articles in this study was conducted systematically using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. This approach was used to ensure that the stages of searching, screening, evaluating, and selecting articles were conducted in a transparent, structured, and academically accountable manner. The research focus was directed toward articles relevant to the themes of artificial intelligence (AI), sustainability assurance, audit quality, ESG governance, and digital transformation in the audit profession in developing countries. Through the application of the PRISMA method, the retrieved articles could be selected more objectively based on the established inclusion and exclusion criteria. The stages of the article identification and selection process are presented in the following figure 1 (Rethlefsen and Page 2022).

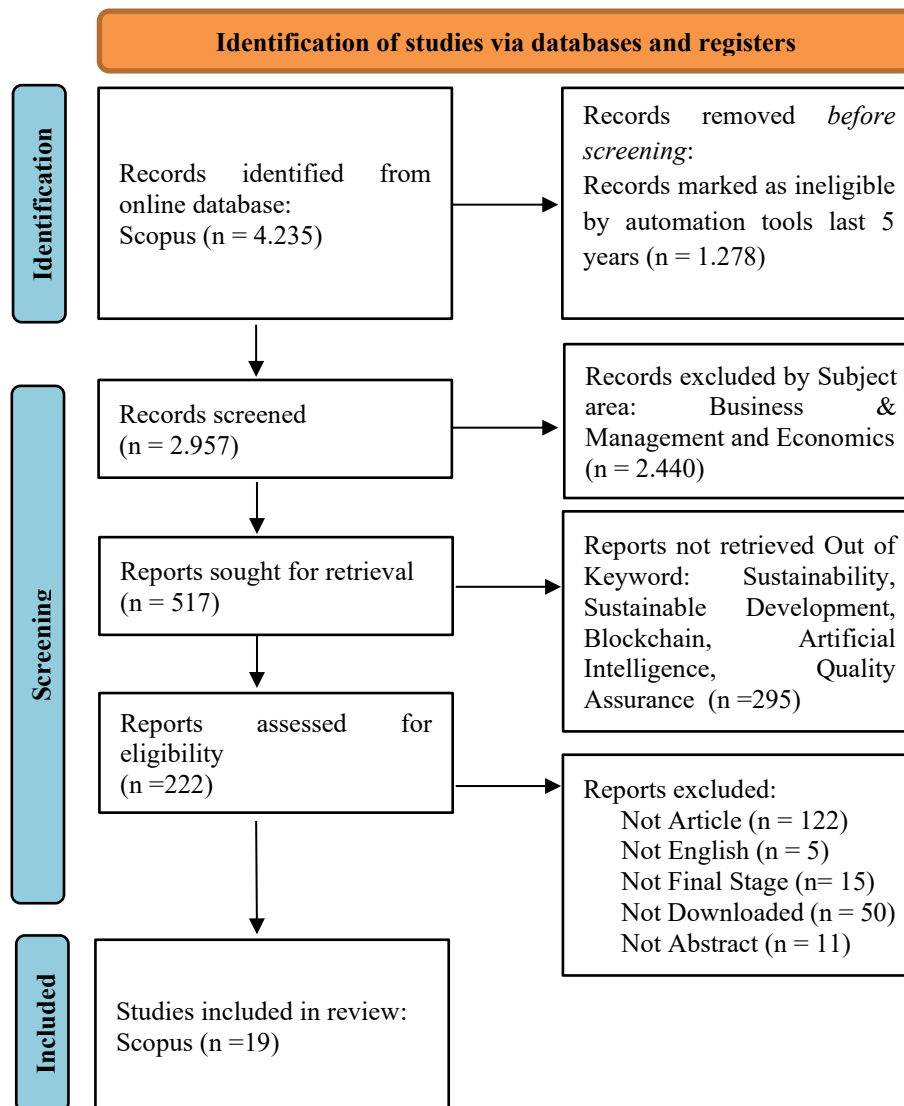


Figure 1. Prisma Diagram. Source: Develop by The Authors

Figure 1 illustrates the article identification and selection process employed in this study. The identification stage began with a comprehensive search of the Scopus database, which initially yielded 4,235 articles related to artificial intelligence, sustainability, auditing, ESG, and digital governance. Subsequently, an initial screening process was conducted using automation tools by limiting publications to the most recent five-year period. As a result, 1,278 articles were excluded because they did not meet the temporal criteria established for the study. This step was undertaken to ensure that the selected literature adequately reflected the latest developments in digital audit transformation, AI competency, and sustainability assurance, which have evolved significantly alongside the growing emphasis on digitalization and ESG governance in recent years. Following this process, 2,957 articles remained and proceeded to the screening stage based on relevant subject areas, namely Business, Management, and Economics.

During the screening stage, 2,440 articles were excluded because they did not fall within the disciplinary scope aligned with the research objectives. This procedure was conducted to maintain the relevance of the selected studies to auditing, sustainability assurance, and auditor AI competency, thereby avoiding literature from less relevant fields. After the subject-area screening, 517 articles advanced to the retrieval stage. At this stage, a more detailed evaluation was conducted based on the relevance of key research topics, including sustainability, sustainable development, blockchain, artificial intelligence, quality assurance, ESG assurance, and digital auditing. The evaluation resulted in the exclusion of 295 articles that did not directly address the primary focus of the study, particularly the relationship between auditor AI competency and sustainability assurance quality in emerging markets. This stage was essential because many studies discussed sustainability or artificial intelligence in general without linking these topics to the auditing and assurance profession.

Subsequently, 222 articles entered the eligibility stage and were assessed through abstract screening and full-text review based on the predefined inclusion and exclusion criteria. During this phase, studies that were irrelevant to the research topic, not published in English, unavailable in full text, lacking abstracts, or not considered final-stage publications were systematically excluded. The exclusion process resulted in the removal of 122 articles due to topic irrelevance, 5 non-English articles, 15 articles that were not final-stage publications, 50 articles with inaccessible full texts, and 11 articles without complete abstracts. Following the completion of all screening and eligibility procedures, 19 articles satisfied all selection criteria and were included in the final systematic literature review. These studies demonstrated strong relevance to the themes of AI competency, digital assurance ecosystems, ESG governance, sustainability assurance quality, and the challenges of digital transformation within the auditing profession in emerging markets.

3.6 Bibliometric Analysis and Visualization

Bibliometric analysis was employed in this study to identify research development patterns, thematic trends, keyword relationships, and future research directions related to artificial intelligence (AI), sustainability assurance, audit quality, ESG governance, and digital transformation within the auditing profession. The bibliometric approach was selected because it provides quantitative and visual insights into the intellectual structure of research surrounding the topic *Future-Ready Auditors: The Impact of AI Competency on Sustainability Assurance Quality in Emerging Markets*. Bibliometric data were derived from the articles that successfully passed the systematic literature review selection process within the Scopus database. Subsequently, article metadata, including titles, abstracts, author keywords, index keywords, authors, source titles, and publication years, were extracted for further analysis. This analysis aimed to identify relationships among research concepts, dominant themes, and emerging trends concerning auditor AI competency and sustainability assurance in emerging markets.

Bibliometric visualization was conducted using bibliometric mapping software to examine keyword relationships through co-occurrence analysis, author collaboration patterns through co-authorship analysis, and thematic developments based on networks of interconnected concepts. Through this visualization process, the study identified several dominant themes, including artificial intelligence, ESG assurance, blockchain, audit quality, digital governance, sustainability reporting, and Quality 4.0, all of which are closely associated

with the transformation of the auditing profession in the digital era. Furthermore, bibliometric analysis facilitated the identification of research gaps, emerging research trends, and opportunities for advancing the concept of future-ready auditors within the context of sustainability assurance quality. Therefore, the bibliometric approach served not only as a literature mapping tool but also as a foundation for strengthening the conceptual synthesis and future research directions regarding auditor AI competency in emerging markets.

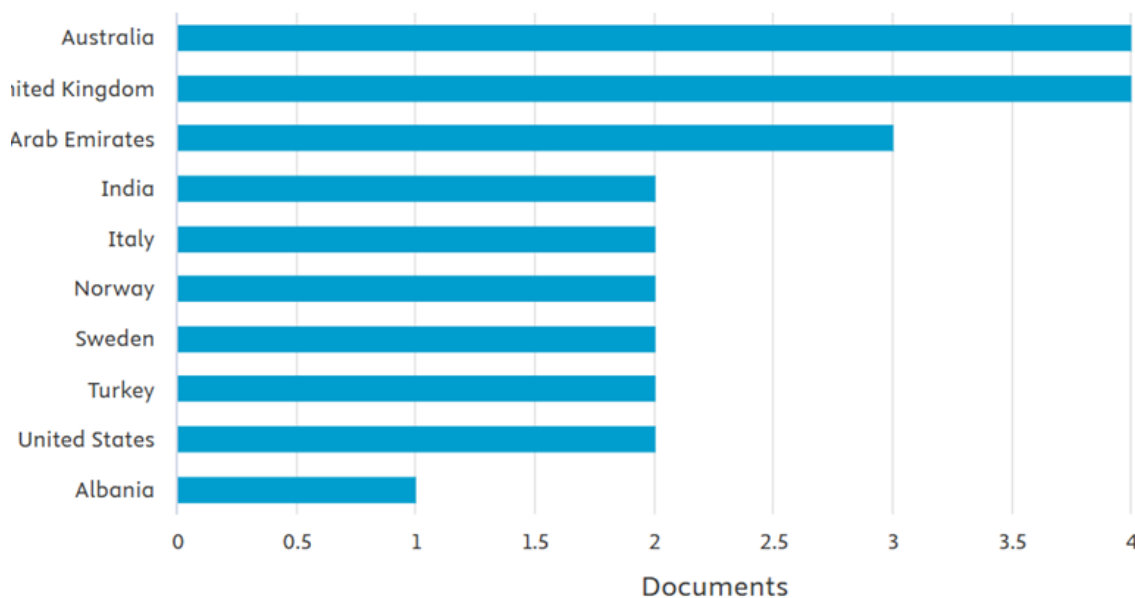


Figure 2. Article Publications in Countries

The bar chart illustrates the distribution of publications by country contributing to research on artificial intelligence, sustainability assurance, audit quality, and digital transformation within the auditing profession. Australia and the United Kingdom emerged as the leading contributors, each producing four publications, followed by the United Arab Emirates with three publications. The dominance of these countries reflects a strong academic interest in the development of digital governance, ESG assurance, sustainability reporting, and the implementation of AI-based technologies in modern auditing systems. Furthermore, countries such as India, Italy, Norway, Sweden, Turkey, and the United States each contributed two publications, indicating that research on auditor AI competency and sustainability assurance quality is expanding across both developed economies and emerging markets.

In contrast, Albania recorded the lowest publication contribution, with only one document. Nevertheless, the diversity of countries represented in the chart demonstrates that issues related to digital auditing transformation, ESG governance, and sustainability assurance have become global and multidisciplinary concerns. The participation of developing and emerging economies, including the United Arab Emirates, India, Turkey, and Albania, suggests that emerging markets are increasingly engaging in research on digital assurance ecosystems and auditor AI competencies to enhance assurance quality and reporting transparency. This

trend reflects growing recognition of the importance of digital technologies and sustainability governance in strengthening organizational accountability and stakeholder confidence.

Overall, the distribution of publications highlights that research on future-ready auditors, AI competency, and sustainability assurance quality is developing on an international scale. The concentration of studies in countries with strong commitments to digital transformation, governance innovation, and sustainability practices suggests that these factors play a significant role in shaping contemporary auditing research. At the same time, the growing involvement of emerging markets indicates an increasing effort to adapt auditing practices to the challenges and opportunities presented by digital transformation, ESG governance, and sustainability assurance in the global business environment.

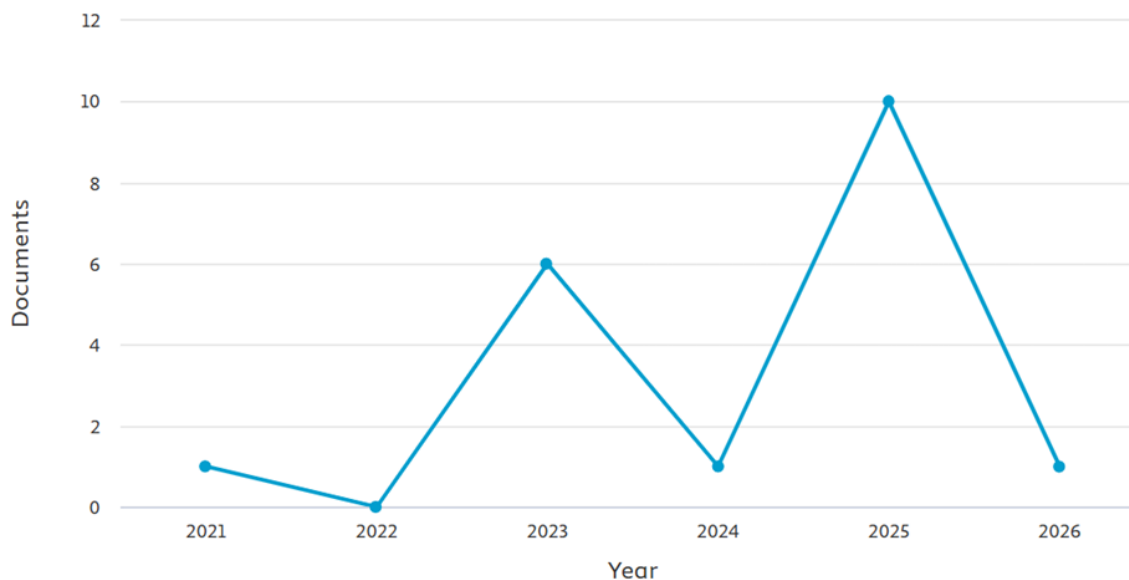


Figure 3. Article Publications by Year

Figure 3 illustrates the trend in research publications related to artificial intelligence, sustainability assurance, audit quality, and digital transformation in the auditing profession during the period 2021–2026. Based on the chart, the number of publications exhibited considerable fluctuations over the years. In 2021, only one publication was identified, followed by a decline in 2022 when no relevant publications were recorded. Subsequently, the number of publications increased substantially in 2023, reaching six documents, indicating growing academic interest in topics such as AI competency, ESG assurance, and digital governance within the contexts of auditing and sustainability reporting. However, the number of publications decreased again in 2024 to a single document before reaching its highest level in 2025 with a total of ten publications.

The significant increase in publications during 2025 suggests that research on future-ready auditors, sustainability assurance quality, and the implementation of artificial intelligence in the auditing profession has become an increasingly important and rapidly developing area of inquiry. This trend is consistent with the growing global emphasis on ESG

reporting, transparency, accountability, and digital transformation within modern assurance systems. Moreover, technological advancements such as artificial intelligence, blockchain, cloud computing, and Quality 4.0 have stimulated extensive scholarly interest in understanding how auditor competencies must evolve to meet the challenges of the digital era. These developments have encouraged researchers to investigate the role of emerging technologies in enhancing audit effectiveness, governance quality, and sustainability assurance practices.

In contrast, the number of publications identified in 2026 declined to one document. This decrease is likely attributable to the fact that the publication year is still in progress and many recently published studies may not yet have been fully indexed in academic databases. Therefore, the lower publication count should not necessarily be interpreted as a decline in scholarly interest. Rather, it may reflect the time lag associated with the indexing and dissemination of newly published research. Overall, the publication trend demonstrates that studies focusing on auditor AI competency and sustainability assurance quality have experienced substantial growth in recent years and have emerged as important themes within contemporary auditing, governance, and sustainability research. The increasing volume of publications highlights the growing recognition of digital transformation as a critical driver of change in the auditing profession and underscores the importance of developing future-ready auditors capable of operating effectively within increasingly technology-enabled assurance environments.

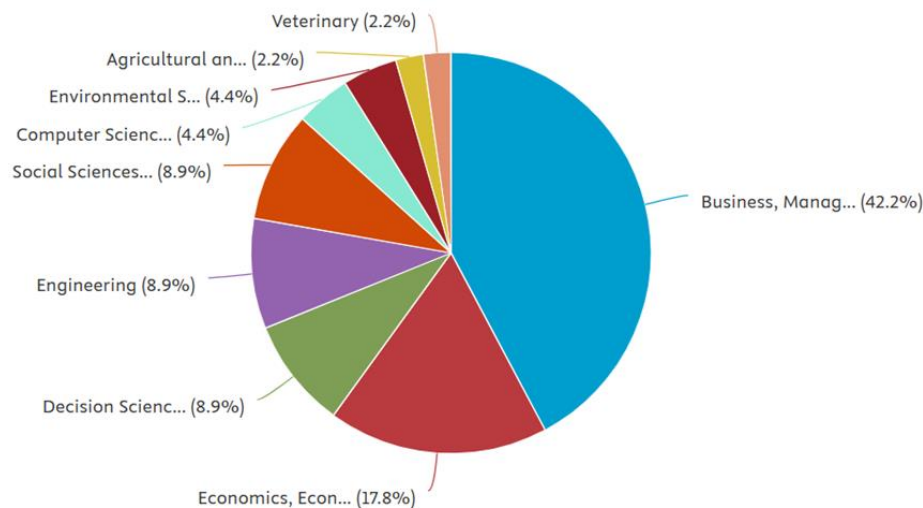


Figure 4. Article Publications by Subject Area

The subject area distribution shows that research on artificial intelligence, sustainability assurance, audit quality, and digital transformation is highly multidisciplinary. Business, Management and Accounting dominates the literature with 42.2% of publications, highlighting a strong focus on auditing, governance, sustainability reporting, and digital transformation. Economics, Econometrics and Finance ranks second with 17.8%, reflecting growing interest in sustainable finance, ESG governance, and assurance quality. Decision Sciences,

Engineering, and Social Sciences each contribute 8.9%, indicating the integration of technological, organizational, and decision-making perspectives in sustainability assurance research. Computer Science and Environmental Science each account for 4.4%, emphasizing the role of AI, digital systems, and sustainability monitoring technologies in modern assurance practices. Overall, the findings demonstrate that future-ready auditors and sustainability assurance quality have evolved into interdisciplinary research areas that combine accounting, economics, governance, technology, and sustainability perspectives.

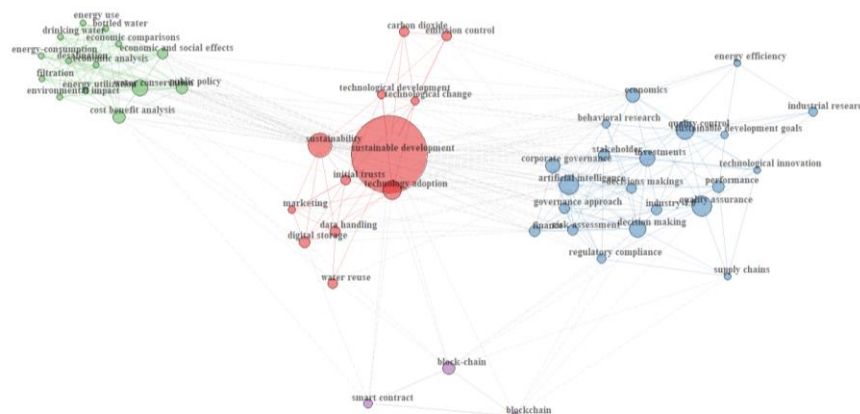


Figure 5. R Studio Visualisation 2026

Figure 5 presents the keyword co-occurrence network, illustrating the relationships among research topics related to artificial intelligence, sustainability assurance, audit quality, ESG governance, and digital transformation within the auditing profession. The network reveals several interconnected clusters that collectively form a multidisciplinary research structure. The red cluster is centered on themes such as *sustainable development*, *sustainability*, *technology adoption*, and *technological change*, indicating that a substantial portion of the literature focuses on how digital technologies and artificial intelligence contribute to the achievement of sustainability objectives and the transformation of modern governance systems. The strong connections among the nodes within this cluster suggest that the development of sustainability assurance is closely linked to digital transformation, data management, and the increasing adoption of emerging technologies in contemporary organizations. Furthermore, the presence of keywords such as *carbon dioxide*, *emission control*, and *water reuse* highlights the growing importance of sustainability monitoring and environmental accountability within technology-enabled assurance ecosystems.

The *blue cluster* demonstrates strong relationships among *artificial intelligence*, *quality assurance*, *corporate governance*, *decision making*, *risk assessment*, *regulatory compliance*, and *sustainable development goals*. The prominence of these nodes indicates that research on AI competency and sustainability assurance quality is increasingly situated within the contexts of governance systems, regulatory compliance, and technology-driven assurance enhancement. The dense interconnections among these keywords suggest that artificial intelligence is being widely utilized to improve auditability, transparency, predictive assessment, and decision-making processes within modern assurance systems. This finding reflects the growing

recognition of AI as a strategic tool for strengthening assurance effectiveness and governance performance. In addition, the *purple cluster*, consisting of keywords such as *blockchain*, *blockchain*, and *smart contract*, indicates that blockchain technology is increasingly viewed as a critical mechanism for creating more transparent, immutable, and trustworthy assurance systems. Through digital verification processes and real-time monitoring capabilities, blockchain-based solutions have the potential to enhance the reliability, traceability, and integrity of sustainability reporting and assurance practices.

The emergence of this cluster reflects the growing interest in leveraging distributed ledger technologies to address challenges related to data authenticity, accountability, and stakeholder trust. Meanwhile, the *green cluster* focuses primarily on sustainability resource management themes, including *water conservation*, *energy consumption*, *cost-benefit analysis*, and *economic analysis*. This cluster suggests that sustainability assurance research is expanding beyond governance and reporting issues to encompass the assessment of resource efficiency and environmental performance. The inclusion of these topics highlights the role of assurance mechanisms in supporting sustainable resource utilization and measuring organizational contributions to environmental sustainability objectives. Overall, the keyword co-occurrence network demonstrates that current research is moving toward an integrated framework that combines artificial intelligence, governance systems, blockchain technology, and sustainability assurance. The interconnected nature of these themes indicates that the future of auditing is increasingly shaped by digital transformation and ESG governance requirements. Consequently, future-ready auditors are expected to possess strong AI competencies, digital capabilities, and technological expertise to effectively support assurance quality, transparency, and accountability within rapidly evolving digital and sustainability-oriented environments.

Table 2. Group Item by Cluster VOSviewer

Cluster	Refined Keywords	Number of Items
Cluster 1	accident prevention; blockchain; compliance; cost benefit analysis; decentralised; digital storage; due diligence; health and safety; health risk; health risks; large datasets; learning systems; machine learning; robust detection; smart contract; technology adoption; worker detection; worker safety; workers detection; workers safety; workers' conditions; working hours	22 Items
Cluster 2	artificial intelligence; corporate governance; customer satisfaction; economics; ethics; governance approach; industrial management; industrial policy; information systems; natural language processing; network analysis; performance; public policy; quality assurance; regulatory approach; regulatory compliance; risk assessment; semantic network analysis; stakeholder; stakeholder governance; sustainable development	21 Items
Cluster 3	circular economy; computer aided analysis; decision making; digitalization; ESG; financial performance; industrial technology; industry 4.0; investment; investments; narratives; risk management; SDG; SDGs; social development; strategic approach; strategic investments; sustainable strategic investment	18 Items

Cluster	Refined Keywords	Number of Items
Cluster 4	agricultural productions; agricultural worker; agriculture; artificial intelligence (AI); big data; commerce; data analytics; data handling; farmer; farmers; farming system; finance; fintech; initial trusts; market transition; marketing; production practice; sustainability; sustainable agricultural; sustainable agriculture; system change	21 Items

Source: Processed by authors through VOSviewer, 2026

Based on the VOSviewer Group Item by Cluster analysis, research on artificial intelligence, sustainability assurance, audit quality, and digital transformation is organized into four interconnected clusters. Cluster 1 focuses on the application of machine learning, blockchain, and smart contracts to enhance transparency, compliance, traceability, and ESG monitoring within modern assurance systems. Cluster 2 highlights the role of artificial intelligence and governance systems in improving accountability, decision-making, risk management, and sustainability assurance effectiveness. Cluster 3 emphasizes the relationship between digital transformation, ESG practices, Industry 4.0, and strategic decision-making in supporting organizational sustainability and performance. Cluster 4 concentrates on the use of artificial intelligence, big data, and analytics to improve sustainability monitoring and performance management across financial and non-financial sectors. Overall, the findings indicate that contemporary research is increasingly moving toward the integration of AI, blockchain, governance systems, and sustainability assurance, underscoring the growing importance of AI competency and digital capability in enhancing assurance quality and governance effectiveness.

Table 3. Selected Keywords

Keyword	Occurrences	Total Link Strength
Sustainable Development	15	95
Sustainability	23	70
Artificial Intelligence	9	57
Technology Adoption	3	56
Finance	3	56
Digital Storage	2	53
Corporate Governance	2	48
Governance Approach	2	48
Risk Assessment	2	48
Artificial Intelligence (Ai)	3	46
Decision Making	4	41
Blockchain	14	39
Decision-Making	2	35
Industry 4.0	3	33
Investments	2	32

Keyword	Occurrences	Total Link Strength
Block-Chain	2	31
Risk Management	3	31
Sdgs	2	30
Digitalization	1	29
Esg	1	29
Financial Performance	1	29
Industrial Technology	1	29
Strategic Approach	1	29
Strategic Investments	1	29
Sustainable Strategic Investment	1	29
Marketing	2	28
Compliance	1	27
Cost Benefit Analysis	1	27

Source: Processed by author through VOSviewer

Based on the keyword co-occurrence analysis, sustainable development emerged as the most influential keyword, indicating that it serves as the central theme connecting research on artificial intelligence, sustainability assurance, governance systems, and digital transformation. Keywords such as sustainability, artificial intelligence, technology adoption, and blockchain further demonstrate that the integration of digital technologies into sustainability governance and assurance systems has become a major focus of contemporary studies. The strong relationships among these keywords suggest that prior research has extensively examined the roles of AI, governance approaches, risk assessment, and quality assurance in enhancing transparency, accountability, and ESG reporting effectiveness. Additionally, the presence of keywords such as Industry 4.0, digitalization, corporate governance, compliance, and risk management reflects the growing adoption of digital governance and intelligent technologies in modern assurance practices. Several emerging topics, including auditor AI competency, blockchain-based assurance systems, predictive risk assessment, and digital assurance ecosystems, also indicate promising directions for future research despite their relatively limited coverage in the existing literature. Overall, the findings reveal an increasing convergence of artificial intelligence, blockchain technology, sustainability governance, and digital auditing, highlighting the critical role of digital transformation in improving sustainability assurance and governance effectiveness.

4. RESULT AND DISCUSSION

Based on a synthesis of 19 peer-reviewed articles, it is evident that the advancement of digital transformation has brought significant changes to auditing and sustainability assurance practices, particularly in the context of emerging markets. Most studies indicate that the implementation of artificial intelligence (AI), blockchain, cloud systems, big data analytics, and other digital technologies plays a crucial role in enhancing transparency, accountability, auditability, and the effectiveness of sustainability assurance. Additionally, various studies emphasize that future auditors must possess AI competency, digital capability, and technology

readiness to adapt to an increasingly complex and data-driven business environment. On the other hand, previous research has largely focused on technological and digital system aspects, while studies specifically linking auditors' AI competencies to the quality of sustainability assurance—particularly in emerging markets—remain very limited. Therefore, this literature synthesis highlights a strong research opportunity to develop an understanding of how auditors' AI competencies can support improvements in the quality of sustainability assurance in addressing governance challenges, ESG reporting, and digital transformation in developing countries.

Table 4. The Result of Literature Analysis

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
1	<i>The AI-policy-governance nexus: How regulation and AI shift corporate governance toward stakeholders</i> – (Cordeiro, Adomaitis, and Huang 2026)	Explains how AI and sustainability regulations are driving the transformation of corporate governance toward stakeholder accountability, as well as ESG disclosure and assurance.	A mixed method combining corpus linguistics and semantic network analysis.	Stakeholder Theory, Shareholder Theory, Institutional Governance Perspective.	AI plays a role in enhancing transparency, disclosure, traceability, and assurance within ESG systems, thereby strengthening corporate governance and sustainability accountability. This is highly relevant to AI-based sustainability assurance quality and governance auditors.
2	<i>Formation of an ESG Management System Based on Digital Analytics</i> – (Kniaz et al. 2026)	Developing a digital analytics-based ESG management system to improve resource management and ESG measurement in the agricultural sector.	Statistical analysis of economics and mathematical modeling of economics.	Sustainable Development Framework, ESG Management, Digital Analytics Perspective.	Digital analytics can transform data resources into ESG indicators that can be used in audits, monitoring, and sustainability assessments. This is relevant because it supports the concept of AI/digital competency in sustainability assurance.
3	<i>Artificial Intelligence in Trauma and Emergency Surgery: A Quantitative Study of Perceived Technology Acceptance</i> – (Dal Mas et al. 2026)	Analyzing professionals' perceptions of AI adoption using the technology acceptance model and responsible AI governance.	A quantitative survey of 624 doctors from 72 countries.	Unified Theory of Acceptance and Use of Technology (UTAUT).	AI competency and acceptance are influenced by governance, accountability, and trust. Although the context is healthcare, this article is theoretically relevant to a future AI competency and acceptance framework for auditors.
4	<i>Revolutionizing Audit Practice in Emerging</i>	Analyzing the impact of AI on the efficiency and	A cross-sectional survey of 356	Agency Theory, Theory of Inspired	AI enhances the efficiency and effectiveness of audits, strengthens

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
	<i>Economies: The Role of Artificial Intelligence in Enhancing the Audit of Consolidated Financial Statements</i> – (Sawayya et al. 2026)	effectiveness of audits of consolidated financial statements in an emerging economy (Lebanon).	auditors using Structural Equation Modeling (SEM).	Confidence, Technology Acceptance Model (TAM).	audit innovation in emerging markets, and supports sustainable audit practices. This article is highly relevant to auditors' AI competencies and audit quality.
5	<i>Digital Technology and Sustainable Corporate Reporting and Disclosure Practices: A Bibliometric Review</i> – (Aldboush et al. 2026)	Exploring the transformation of corporate reporting and sustainability disclosure through AI, blockchain, big data, and cloud computing.	A bibliometric review using Web of Science, Scopus, and Dimensions.	Sustainability Reporting Perspective, ESG Reporting Framework, Digital Transformation Perspective.	Digital technology strengthens transparency, audit trails, ESG disclosures, stakeholder engagement, and governance reporting. This is particularly relevant for sustainability assurance and reporting systems powered by artificial intelligence.
6	<i>Overcoming Resistance to Change: Artificial Intelligence in the Energy Sector</i> – (Lambert 2026)	Examining the application of artificial intelligence (AI), governance, workforce competency, and auditable AI implementation in the energy sector.	A multi-case qualitative case study involving interviews, surveys, and document analysis.	Dynamic Capabilities Perspective, AI Readiness, Human-Centered Governance.	AI adoption requires competency building, governance assurance, explainability, and auditable process standards. This is relevant to AI competency and governance assurance, even though it is not a direct audit context.
7	<i>Internal Control Systems and Technological Capabilities as Drivers of Bank Risk Management for Advancing Sustainable Development</i>	Examining the impact of internal control systems, AI, and big data on risk management, institutional	Partial Least Squares Structural Equation Model (PLS-SEM) on 448 senior bank managers.	COSO Framework, Resource-Based View, Dynamic Capability Perspective.	AI and big data enhance the effectiveness of risk management and institutional transparency, which support sustainable governance and SDG 16. This is highly relevant to

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
	<i>Goal 16 – (Sang and Anh 2026)</i>	transparency, and SDG 16 in Vietnam's banking sector.			governance assurance, AI capabilities, and the quality of sustainability assurance in emerging markets.
8	<i>Using Machine Learning and Blockchain for Trusted Detection and Monitoring of Excessive Working Hours in Factories – (Hawashin et al. 2025)</i>	Developing an AI- and blockchain-based system for monitoring work hours in a transparent, traceable, and auditable manner.	Machine learning (YOLOv8), blockchain integration, smart contracts, dan performance evaluation.	AI Governance, OECD Due Diligence Guidance, Trustworthy AI Monitoring Framework.	Blockchain and artificial intelligence (AI) enhance transparency, traceability, accountability, and reliable compliance monitoring in sustainable labor governance. This is relevant for sustainability assurance and AI-powered audit ecosystems.
9	<i>Using Composable NFTs and Blockchain for the Creation of EV Battery Digital Passports with Sustainability and Traceability Features – (Hasan et al. 2025)</i>	Developing a blockchain-based digital passport for sustainability monitoring and traceability of the EV battery lifecycle.	Design Research (DSR), blockchain architecture, smart contracts, sustainability scoring.	Blockchain Transparency Perspective, Circular Economy Framework, Sustainability KPI Framework.	The system enhances auditability, traceability, sustainability assurance, and transparency through immutable digital records. It is relevant to the digital assurance ecosystem and technology-based sustainability reporting assurance.
10	<i>Blockchain-Enabled ESG for Secure and Transparent Sustainability Accounting – (R. V. Patil and Kashid 2025)</i>	Mengkaji integrasi blockchain dalam ESG reporting untuk menciptakan sustainability accounting yang immutable, auditable, dan transparent.	Structured literature review and conceptual framework analysis.	Blockchain Governance Theory, Digital Assurance Framework, Sustainability Accounting Perspective.	Blockchain enhances data reliability, real-time reporting, auditability, and anti-greenwashing measures in sustainability reporting. It is highly relevant to digital technology-based sustainability assurance quality.

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
11	<i>Decentralized Autonomous Organizations As Emerging Economic Entities in Accounting and Governance Frameworks</i> – (R. V. Patil et al. 2025)	Analyzing DAOs, smart contracts, and blockchain in governance, accounting transparency, and decentralized financial monitoring.	Conceptual analysis and comparative governance framework.	Institutional Theory, Blockchain Governance, Decentralized Finance Framework.	DAOs enhance transparency, real-time auditability, and decentralized governance through blockchain-based accounting systems. This is relevant for the future audit ecosystem and digital assurance transformation.
12	<i>Exploring AI Application in ESG Assurance: Insights from UTAUT and Perceived Risk Theory</i> – (Anal et al. 2025)	Analyzing the factors influencing the adoption of AI in ESG assurance in Vietnam, with a focus on auditors, assurance providers, and institutional readiness.	Literature synthesis and theoretical framework analysis.	Unified Theory of Acceptance and Use of Technology (UTAUT) and Perceived Risk Theory (PRT).	AI enhances the effectiveness of ESG assurance through data analytics, anomaly detection, and continuous auditing; however, its adoption is influenced by perceived risk, governance, and institutional capacity. This is particularly relevant to auditors' AI competencies and the quality of sustainability assurance in emerging markets (Vietnam).
13	<i>The Moderating Role of Finance, Accounting, and Digital Disruption in ESG, Financial Reporting, and Auditing: A Triple-Helix Perspective</i> – (Lulaj and Brajković 2025)	Analyzing the impact of finance, accounting, and digital disruption on the integration of ESG, audit, sustainability, and financial reporting through a triple-helix perspective.	Quantitative research using Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and moderation analysis of 200 expert respondents.	Triple-Helix Theory, ESG Integration Framework, Digital Transformation Perspective.	Digital disruption and innovation in finance and accounting are strengthening the integration of ESG, sustainability audits, and reporting transparency. This is closely linked to auditors' digital competencies and the sustainability assurance ecosystem.

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
14	<i>Business Ethics, Leadership, and Sustainability in Light of Auditing: The Mediating Impact of Cloud-Based Managerial Accounting Practices Toward Audit Quality</i> – (Tawfeeq Yousif Alabdullah, Ries Ahmed, and Khalid Salih 2025)	Examining the influence of ethical auditing, sustainability control, cloud-based managerial accounting, and leadership on audit quality in developing countries.	PLS-SEM analysis of 147 public accountants in Iraq.	Ethical Auditing Theory, Leadership Theory, Sustainability Control Perspective, Digital Transformation Framework.	Cloud-based managerial accounting improves audit quality through transparency, continuous monitoring, and digital access to data. This is relevant to AI/digital auditor competencies and technology-enabled audit quality in emerging markets.
15	<i>Blockchain-enabled Road Vehicle Emissions Monitoring: A Secure, Scalable and Private Framework</i> – (O'Brien et al. 2025)	Developing a blockchain-enabled framework for emissions monitoring that is secure, auditable, scalable, and GDPR-compliant.	An experimental blockchain architecture using Hyperledger Fabric and EPIC infrastructure simulation.	Blockchain Governance Framework, IoT Assurance Framework, Digital Identity Perspective.	Blockchain enhances auditability, transparency, compliance with emissions standards, and real-time sustainability monitoring. This is relevant to sustainability assurance technology and trusted reporting infrastructure.
16	<i>Digitalised Validation Systems as an Enabler for Quality 4.0 within a Medical Device Manufacturer</i> – (McDermott et al. 2024)	Investigating the implementation of digital validation systems as part of Quality 4.0 and sustainability in the medical device industry.	A 3-year longitudinal case study using Design for Six Sigma.	Quality 4.0, Industry 4.0, Digitalisation Framework.	Digital validation systems improve audit readiness, data integrity, sustainability, compliance quality, and continuous monitoring. This is particularly relevant to the transformation of digital assurance and audit quality driven by artificial intelligence.

No	Research Title and Author (Year)	Focus Areas and Objectives	Research Methodology	Theories Used	Key Findings
17	<i>Ethical Considerations of Service Organizations in the Information Age</i> – (Camilleri et al. 2024)	Examining ethical leadership, AI, big data, ESG reporting, sustainability accounting, and assurance in service organizations in the digital age.	Systematic Literature Review and thematic analysis of articles in Scopus.	Business Theory, Responsibility Perspective, Information Framework.	Ethics ESG Age
18	<i>Financial Services Industry in Digital Era: Emerging Cyber Security and Sustainability Perspectives</i> – (Alfityani et al. 2024)	Discussing the digital transformation of the financial services industry, cybersecurity, sustainability risks, and sustainability assurance reporting.	Conceptual review paper.	Sustainable Perspective, Finance Transformation Perspective.	Finance Digital
19	<i>NIR Technology for Non-Destructive Monitoring of Apple Quality During Storage</i> – (Włodarska et al. 2024)	Using NIR technology and pattern recognition for quality assurance and sustainability monitoring in the food supply chain.	Quantitative experimental research using PCA and PLS-DA.	Industry 4.0 and Intelligent Monitoring Framework.	Quality

Based on the synthesis of the 19 reviewed articles, the majority of studies indicate that digital transformation through the adoption of artificial intelligence (AI), blockchain, cloud computing, big data analytics, and Quality 4.0 has fundamentally transformed the paradigms of auditing and sustainability assurance, making them more integrated, real-time, transparent, and data-driven. Several studies emphasize that digital technologies enhance auditability, transparency, accountability, and the effectiveness of monitoring sustainability reporting and ESG assurance (Hawashin et al. 2025; McDermott et al. 2024; R. V. Patil and Kashid 2025). Furthermore, the implementation of AI and digital systems has been found to strengthen audit quality through continuous auditing, automated validation systems, and more effective data integrity management (Sawaya et al. 2026; Tawfeeq Yousif Alabdullah, Ries Ahmed, and Khalid Salih 2025). Within the context of sustainability assurance, various studies suggest that modern organizations are increasingly required to provide credible ESG reporting and sustainability disclosures supported by digital technologies in order to enhance stakeholder trust and governance legitimacy (Camilleri et al. 2024; Cordeiro et al. 2026). These findings indicate that technological advancement not only transforms assurance systems but also requires auditors to possess digital competencies and AI capabilities to perform assurance functions effectively in the era of digital transformation.

On the other hand, the synthesis findings also reveal that emerging markets face more complex challenges in implementing digital assurance ecosystems and sustainability governance. Several studies report that developing countries continue to experience limitations related to institutional readiness, digital infrastructure, and insufficient AI competency and technological readiness among auditing professionals (Anal et al. 2025; Sang and Anh 2026; Sawaya et al. 2026). These conditions contribute to suboptimal sustainability assurance quality in emerging markets despite the increasing adoption of digital technologies. Moreover, the majority of prior studies have concentrated on technological development, ESG systems, and digital governance, while research directly examining the relationship between auditor AI competency and sustainability assurance quality remains relatively scarce. This gap is particularly important because several studies have emphasized that auditors' capabilities in understanding AI, data analytics, cloud systems, and governance technologies are critical factors in enhancing assurance quality, transparency, and accountability in sustainability reporting (Aldboush et al. 2026; Kniaz et al. 2026; Lulaj and Brajković 2025). Therefore, research on future-ready auditors is highly relevant for explaining how auditor AI competency can contribute to improving sustainability assurance quality, particularly in emerging markets that are experiencing accelerated digital transformation and increasing demands for ESG governance.

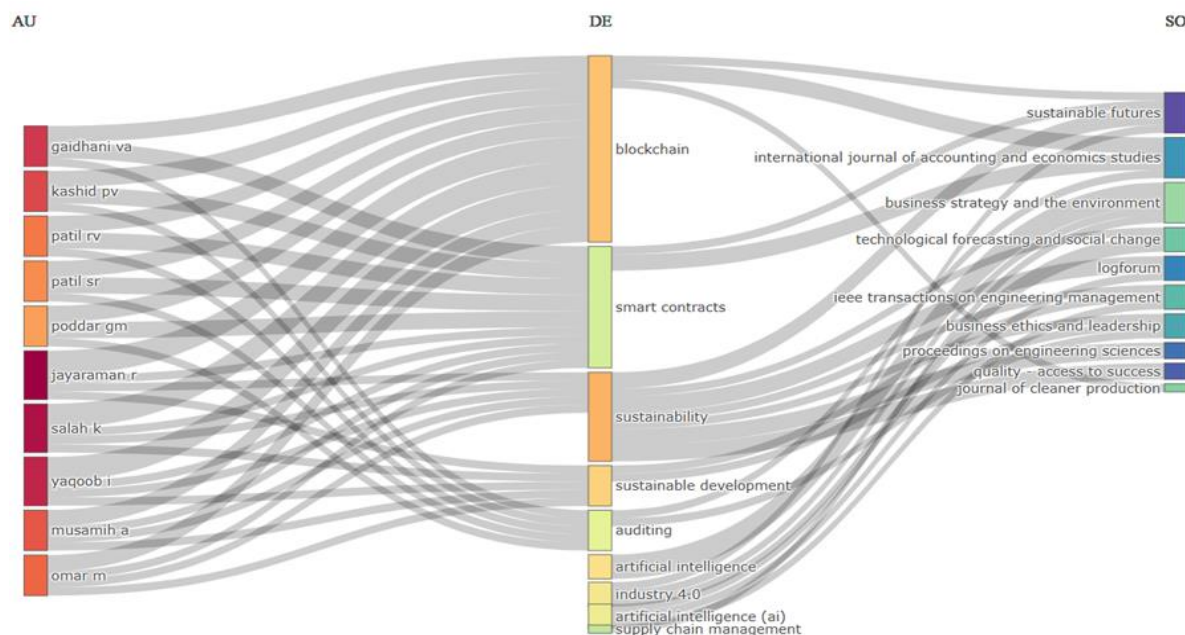


Figure 6. Sankey Diagrams

Figure 6 presents a three-field plot that visualizes the relationships among authors (AU), research keywords or themes (DE), and publication sources (SO). The diagram indicates that research on artificial intelligence, sustainability assurance, blockchain, and governance systems is predominantly centered on themes such as blockchain, smart contracts, sustainability, sustainable development, and artificial intelligence. The strongest connections are observed for the themes of blockchain and smart contracts, suggesting that these topics have become major focal points in the development of research related to transparency, traceability, compliance systems, and technology-enabled sustainability assurance. Authors such as Patil R.V., Patil S.R., Poddar G.M., and Jayaraman R. appear to make significant contributions to these research streams, particularly in the areas of blockchain governance, sustainability systems, and digital assurance ecosystems.

Furthermore, the diagram reveals strong linkages among artificial intelligence, auditing, Industry 4.0, and sustainability governance within the context of digital transformation in modern organizations. Themes such as artificial intelligence, Industry 4.0, supply chain management, and auditing are connected to multiple journals and researchers, indicating that contemporary research is increasingly focused on leveraging AI and blockchain technologies to enhance assurance quality, governance transparency, risk management, and sustainability reporting. These interconnections demonstrate that digital technologies are no longer viewed merely as analytical tools but have evolved into essential instruments for supporting ESG governance, organizational decision-making, and compliance monitoring in the era of digital transformation. From the perspective of publication sources, journals such as *Business Strategy and the Environment*, *Sustainable Futures*, *Technological Forecasting and Social Change*, *IEEE Transactions on Engineering Management*, and *Journal of Cleaner Production* emerge as the primary outlets publishing research related to sustainability assurance, governance systems, and artificial intelligence.

The prominence of these journals suggests that studies examining the integration of AI, blockchain, sustainability governance, and digital transformation have gained substantial relevance across the disciplines of auditing, sustainability management, engineering management, and organizational governance. Overall, this visualization demonstrates that the current trajectory of research is increasingly directed toward the integration of artificial intelligence, blockchain technology, and sustainability assurance systems to enhance transparency, accountability, and governance quality within modern organizations. The interconnected relationships among authors, research themes, and publication sources further indicate that digital transformation is reshaping the intellectual landscape of auditing and sustainability assurance, highlighting the growing importance of technological competencies and innovative governance approaches in addressing contemporary organizational challenges.

Table 5. Key Issues

Key Issues	Specific Aspect	Source	Citation
AI Competency and Auditor Digital Capability	AI competency and digital capability have become essential skills for auditors in responding to technology-driven auditing transformation and ESG assurance requirements.	(Anal et al. 2025; McDermott et al. 2024; Sang and Anh 2026; Sawaya et al. 2026)	“AI improves audit efficiency and effectiveness”; “AI adoption in ESG assurance depends on institutional capability and technology readiness.”
	Future auditors require competencies in data analytics, AI literacy, cloud systems, and digital governance to support audit quality.	Alabdullah et al. (2025); Lulaj & Brajković (2025)	“Cloud-based managerial accounting practices enhance audit quality through transparency and continuous monitoring.”
	Technology readiness and AI adoption strengthen auditors’ capabilities in conducting continuous auditing and sustainability verification.	Dal Mas et al. (2026); Lambert (2026)	“Competency and AI acceptance are influenced by governance, accountability, and trust.”
Sustainability Assurance Transformation	Sustainability assurance is evolving from traditional approaches toward technology-enabled assurance systems supported by AI and	Patil et al. (2025); Hawashin et al. (2025)	“Blockchain improves auditability, transparency, and anti-greenwashing mechanisms in ESG reporting.”

Key Issues	Specific Aspect	Source	Citation
Governance, Transparency, and Accountability	blockchain technologies.		
	ESG assurance increasingly emphasizes real-time monitoring, traceability, and automated compliance assurance.	Hasan <i>et al.</i> (2025); O'Brien <i>et al.</i> (2025)	"Blockchain-enabled systems provide trusted and auditable sustainability monitoring."
	Sustainability reporting requires more credible assurance systems to enhance stakeholder trust and governance legitimacy.	Camilleri <i>et al.</i> (2024); Cordeiro <i>et al.</i> (2026)	"Organizations are expected to conduct sustainability accounting, reporting, and assurance of ESG performance."
	AI, blockchain, and digital systems enhance transparency, accountability, and auditability in ESG governance.	Patil <i>et al.</i> (2025); Hawashin <i>et al.</i> (2025)	"AI and blockchain improve accountability, transparency, and compliance assurance."
	Digital governance strengthens stakeholder accountability through immutable audit trails and real-time verification systems.	Hasan <i>et al.</i> (2025); Patil <i>et al.</i> (2025)	"Blockchain provides immutable digital records that strengthen sustainability assurance."
	Ethical governance and sustainability accountability have become critical issues in AI-enabled modern assurance systems.	Camilleri <i>et al.</i> (2024); Cordeiro <i>et al.</i> (2026)	"AI shifts corporate governance toward stakeholders and sustainability accountability."

Source: Processed by author through VOSviewer

Discussion

RQ1: How Has Research on Artificial Intelligence and Sustainability Assurance Evolved in the Academic Literature?

The development of research on artificial intelligence and sustainability assurance has increased significantly in recent years, particularly in response to the growing demand for transparency, accountability, and ESG governance within modern organizations. Early studies primarily focused on how digital technologies such as artificial intelligence, blockchain, and digital analytics could enhance monitoring effectiveness, governance systems, and sustainability reporting. Cordeiro *et al.* (2026) demonstrated that artificial intelligence is

transforming the corporate governance paradigm toward a more stakeholder-oriented governance model by improving transparency and sustainability accountability. Similar findings were reported by Aldboush et al. (2026), who argued that digital technologies, including AI, blockchain, and cloud systems, strengthen sustainability disclosure quality and ESG reporting through data-driven reporting mechanisms. Furthermore, Kniaz *et al.* (2026) found that digital analytics improves the effectiveness of ESG management systems and sustainability monitoring within modern organizations. These developments indicate that sustainability assurance research has gradually shifted from traditional approaches toward more integrated, technology-enabled, and data-driven assurance systems.

The literature further reveals that artificial intelligence is increasingly regarded as a critical instrument for improving audit quality, governance capability, and sustainability assurance effectiveness. Sawaya *et al.* (2026) explained that AI adoption in auditing enhances audit efficiency and effectiveness through automated assessment and predictive analytics, particularly in emerging economies. Similarly, Sang and Anh (2026) found that AI implementation in ESG assurance enables auditors to perform anomaly detection, continuous auditing, and sustainability verification more effectively. Alabdullah et al. (2025) also reported that cloud-based managerial accounting and digital systems positively influence audit quality through enhanced transparency and continuous monitoring. In addition, Sang and Anh (2026) demonstrated that AI and big data analytics strengthen institutional transparency and governance systems in supporting the Sustainable Development Goals (SDGs). Collectively, these findings suggest that artificial intelligence is no longer viewed merely as a supporting technology but rather as a strategic element in the transformation of auditing and sustainability governance.

Another notable trend in the literature is the increasing integration of blockchain technology, smart contracts, and sustainability assurance systems. Patil et al. (2025) Patil *et al.* (2025) reported that blockchain improves auditability, traceability, and anti-greenwashing mechanisms in ESG reporting through immutable digital records. This finding is supported by Hasan et al. (2025), who showed that blockchain-based digital passports enhance transparency and sustainability monitoring through traceable verification systems supported by smart contracts. Furthermore, Hawashin et al. (2025) argued that the integration of machine learning and blockchain creates more reliable compliance monitoring systems characterized by greater transparency and accountability within sustainability governance. O'Brien (2021) also found that blockchain-enabled monitoring systems support emissions compliance and real-time sustainability assurance more effectively. These findings indicate that modern sustainability assurance is increasingly moving toward a digital assurance ecosystem that integrates AI, blockchain, and real-time monitoring technologies to improve assurance quality and governance transparency across various industries.

Despite the significant progress in research on artificial intelligence and sustainability assurance, the literature synthesis reveals a notable gap regarding the direct relationship between auditor AI competency and sustainability assurance quality, particularly in emerging markets. Most previous studies have concentrated on technological development, governance systems, ESG reporting, and sustainability monitoring rather than focusing on auditors as key actors in the assurance process. Sawaya et al. (2026) and Anal et al. (2025) identified institutional readiness and digital capability as major challenges in implementing AI-based assurance in developing countries. Additionally, Camilleri et al. (2024) emphasized that

modern organizations require auditors who possess knowledge of AI systems, ESG governance, and digital ethics to support sustainability accountability. Overall, the findings suggest that research on artificial intelligence and sustainability assurance is increasingly characterized by the integration of digital technologies, governance systems, and sustainability reporting. However, studies specifically examining auditor AI competency as a determinant of sustainability assurance quality remain limited, thereby creating substantial opportunities for future research, particularly within emerging markets undergoing rapid digital transformation and ESG governance development.

RQ2: What Is the Role of Auditor AI Competency in Enhancing Sustainability Assurance Quality in the Era of Digital Transformation?

The role of auditor AI competency in enhancing sustainability assurance quality has become increasingly important as ESG reporting, governance systems, and digital assurance ecosystems continue to grow in complexity. Modern auditors are no longer solely responsible for examining traditional financial statements but are also expected to understand artificial intelligence, big data analytics, cloud systems, and automated assurance technologies to support organizational transparency and accountability. Dal Mas et al. (2026) argued that the successful implementation of artificial intelligence largely depends on competency, governance understanding, and trust in digital systems used within assurance processes. Similarly, Lambert (2026) found that AI adoption requires workforce capability and governance readiness to ensure that technology can be effectively utilized in monitoring and assurance systems. These findings indicate that auditor AI competency serves as a critical foundation for digital sustainability assurance because auditors must be capable of interpreting data, understanding digital risks, and conducting assurance evaluations in increasingly technology-driven environments.

Several studies further demonstrate that auditor AI competency contributes significantly to audit quality through predictive analytics, anomaly detection, and real-time continuous auditing capabilities. McDermott et al. (2024) found that digitalized validation systems improve data integrity, audit readiness, and compliance quality through paperless and technology-enabled assurance processes. Likewise, Włodarska et al. (2024) reported that Industry 4.0 technologies and digital monitoring systems facilitate more automated and accurate quality assurance processes for sustainability monitoring. Lulaj and Brajković (2025) also demonstrated that digital disruption and AI capability significantly influence reporting transparency, ESG integration, and governance effectiveness. These findings suggest that auditor AI competency enables assurance processes to become faster, more efficient, and increasingly data-driven, thereby enhancing the reliability and quality of sustainability assurance.

Moreover, auditor AI competency plays a strategic role in strengthening governance transparency and stakeholder accountability within sustainability assurance systems. Patil and Kashid (2025) explained that blockchain and digital governance technologies create stronger auditability and transparency through immutable digital records and anti-greenwashing mechanisms in ESG reporting. Similar findings were presented by Hasan et al. (2025), who demonstrated that blockchain-based sustainability monitoring systems support traceability and real-time verification within assurance processes. Furthermore, Bakarich and O'Brien (2021) found that AI- and blockchain-enabled monitoring systems improve emissions compliance and

sustainability governance through automated digital verification mechanisms. These developments suggest that auditors possessing strong AI competencies are better equipped to understand digital assurance ecosystems and evaluate sustainability performance in a more credible, transparent, and technology-driven manner than traditional assurance approaches.

Nevertheless, the literature also reveals several challenges associated with developing auditor AI competency, particularly within emerging markets characterized by limited institutional readiness and digital infrastructure. Alfityani et al. (2024) emphasized that digital transformation in financial services requires auditors capable of understanding cyber risks, digital governance, and sustainability monitoring systems comprehensively. Furthermore, Camilleri et al. (2024) argued that modern organizations require auditors who not only understand AI technologies but also possess ethical awareness and governance capabilities to perform sustainability assurance effectively. Overall, the findings indicate that auditor AI competency plays a vital role in improving sustainability assurance quality by enhancing auditability, transparency, predictive assessment, and governance effectiveness. However, these competencies require continuous strengthening through improved digital capabilities, AI literacy, and governance understanding to address the challenges of sustainability assurance within increasingly complex digital business environments.

RQ3: What Factors Influence the Effectiveness of AI-Based Sustainability Assurance in Emerging Markets?

The effectiveness of AI-based sustainability assurance in emerging markets is influenced by various factors related to technological readiness, governance quality, and organizational capability to integrate digital systems into modern assurance processes. One of the most frequently discussed factors in the literature is institutional readiness and technology adoption capability. Sang and Anh (2026) explained that the effectiveness of AI and big data applications in governance systems largely depends on the readiness of institutions to establish internal control systems, digital infrastructure, and transparency mechanisms that support sustainable governance. Similarly, Sawaya et al. (2026) found that implementing artificial intelligence in auditing within emerging economies requires organizational readiness and audit innovation capability to maximize audit effectiveness. These findings suggest that successful AI-based sustainability assurance depends not only on technological availability but also on the ability of institutions to create governance environments that support sustainable digital transformation.

Another important factor influencing the effectiveness of AI-based sustainability assurance is the quality of digital governance and regulatory compliance. Cordeiro et al. (2026) argued that AI and sustainability regulations drive governance systems toward more stakeholder-oriented, transparent, and accountable models. Likewise, Aldboush et al. (2026) found that digital technologies such as AI, blockchain, and cloud systems improve ESG disclosure quality and sustainability reporting when supported by appropriate governance frameworks and regulatory systems. Anal et al. (2025) further demonstrated that perceived risk, governance capability, and institutional trust significantly affect the success of AI adoption in ESG assurance. These findings indicate that effective AI-based sustainability assurance requires organizations to establish governance systems capable of maintaining transparency, accountability, and compliance with sustainability standards and ESG regulations.

Beyond governance considerations, human resource quality and auditors' digital competencies are also critical factors supporting AI-based sustainability assurance in emerging markets. Alabdullah et al. (2025) explained that cloud-based managerial accounting and digital systems can enhance audit quality only when supported by auditors who possess sufficient technological expertise and governance knowledge. Similarly, Dal Mas et al. (2026) demonstrated that AI acceptance and implementation effectiveness are strongly influenced by competency, trust, and user understanding of artificial intelligence systems. Lambert (2026) further identified workforce capability and organizational adaptation as key determinants of successful AI governance and digital transformation. These findings suggest that the success of AI-based sustainability assurance in emerging markets requires not only technological investment but also the development of AI literacy, digital capability, and governance understanding among auditors and assurance providers to ensure responsible and effective technology utilization.

Although numerous enabling factors have been identified in the literature, emerging markets continue to face significant challenges in optimizing AI-based sustainability assurance. McDermott et al. (2024) reported that the implementation of digital assurance systems is often hindered by resistance to change, inadequate training, and limited data management capability. Furthermore, Hawashin et al. (2025) found that AI- and blockchain-based sustainability monitoring requires strong trust mechanisms, due diligence systems, and compliance capabilities to operate effectively. Hasan et al. (2025) also emphasized that traceability and digital verification systems require governance standardization and technological interoperability to support sustainability assurance more efficiently. Overall, the findings suggest that the effectiveness of AI-based sustainability assurance in emerging markets is determined by a combination of institutional readiness, governance quality, regulatory compliance, digital capability, and auditor AI competency. Therefore, strengthening digital governance and enhancing technological competencies represent strategic priorities for improving sustainability assurance quality in the era of digital transformation.

RQ4: What Is the Future Direction for Developing Future-Ready Auditors in Addressing ESG Governance, Digital Transformation, and Sustainability Reporting Challenges?

The future direction of development for future-ready auditors indicates a significant shift from the traditional auditor role toward auditors with multidisciplinary capabilities in digital technology, sustainability governance, and strategic analytics. The advancement of digital transformation means that auditors are no longer solely tasked with financial verification but also play a role in ensuring the quality of ESG reporting, sustainability disclosures, and the organization's overall governance transparency. Kniaz et al. 2026; Włodarska et al. (2024) explain that the development of digital analytics and ESG management systems is driving organizations to integrate data-driven technologies into sustainability monitoring and assurance processes. Additionally, Włodarska et al. (2024) found that Industry 4.0 technologies and smart quality monitoring systems can enhance the effectiveness of quality assurance and sustainability controls through digital approaches and automation. These findings indicate that future auditors must possess skills in data interpretation, digital analytics, and sustainability assessment to effectively navigate the evolving technology-driven business environment and ESG governance landscape.

Future developments indicate that future-ready auditors will increasingly rely on the use of blockchain, smart contracts, and digital verification systems to support sustainability assurance and governance transparency. Patil et al. (2025) explain that blockchain-enabled ESG systems enable the creation of more transparent, immutable, and auditable sustainability accounting through digital traceability and anti-greenwashing mechanisms. Additionally, Hasan et al. (2025) found that blockchain-based sustainability monitoring systems support real-time verification and sustainability traceability through the use of smart contracts and digital passports. Research by O'Brien et al. (2021) also indicates that blockchain-enabled monitoring systems strengthen compliance assurance and environmental governance through digital infrastructure-based monitoring systems. Based on this synthesis, it is clear that future auditors will require not only conventional auditing skills but also an understanding of blockchain governance, digital verification, and sustainability technology to ensure the reliability and transparency of modern sustainability reporting.

On the other hand, the development of future-ready auditors will also be influenced by the growing need for governance capabilities, ethical awareness, and sustainability-oriented decision-making in modern organizations. Camilleri et al. (2024) explain that the development of ESG governance and sustainability accountability requires auditors to understand ethical auditing, digital ethics, and stakeholder governance in performing modern assurance functions. Additionally, Alfityani et al. (2024) found that the development of cyber governance, sustainability finance, and digital risk management is driving auditors to develop a more comprehensive understanding of cybersecurity, data governance, and digital compliance systems. Research by Hawashin et al. (2025) also indicates that AI and blockchain-based monitoring systems require strong governance trust, due diligence capabilities, and compliance management to ensure that sustainability assurance operates effectively. In the researchers' view, these conditions indicate that future auditors will evolve into strategic governance advisors who not only focus on assurance but also play a role in maintaining an organization's sustainability accountability, digital transparency, and governance resilience.

Overall, the direction of development for future-ready auditors indicates that the audit profession will become increasingly integrated with artificial intelligence, blockchain technology, sustainability governance, and the digital assurance ecosystem. Future auditors must possess AI competency, digital capability, an understanding of governance, and sustainability literacy in order to adapt to an increasingly complex and digitally-driven business environment. McDermott et al. (2024) emphasize that the implementation of Quality 4.0 and digital assurance systems requires auditors capable of effectively understanding data integrity, automated validation, and digital compliance processes. Additionally, Lulaj and Brajković (2025) explain that digital transformation and ESG integration will continue to drive a paradigm shift in auditing toward more transparent, data-driven, and sustainability-oriented assurance systems. Based on these findings, it can be concluded that the development of future-ready auditors will focus on integrating technological competencies, governance capabilities, sustainability assurance, and strategic decision-making to address the challenges of ESG governance, digital transformation, and sustainability reporting in a more adaptive and sustainable manner.

5. CONCLUSION

This systematic literature review of 19 articles demonstrates that artificial intelligence, blockchain, big data analytics, and digital governance have significantly transformed sustainability assurance and modern auditing practices. AI has evolved into a strategic tool that enhances transparency, accountability, auditability, and sustainability assurance effectiveness through continuous auditing, predictive risk assessment, and automated verification systems. The findings also highlight that auditor AI competency is a critical factor in improving sustainability assurance quality, particularly in addressing the growing complexity of ESG governance and digital transformation. However, emerging markets continue to face challenges related to institutional readiness, digital infrastructure, governance capability, and limited auditor digital competencies. Consequently, strengthening AI literacy, digital capability, governance understanding, and sustainability assurance skills is essential for developing future-ready auditors capable of supporting effective and sustainable assurance practices.

Limitations and Directions for Future Research

This study is limited to articles indexed in the Scopus database and reveals that existing research largely focuses on technological developments rather than the direct relationship between auditor AI competency and sustainability assurance quality. Furthermore, most studies are concentrated in developed countries, leaving emerging market contexts relatively underexplored. Future research should conduct empirical investigations into the effects of auditor AI competency, digital capability, and governance quality on sustainability assurance effectiveness across industries and emerging economies. Further studies may also examine the role of generative AI, blockchain assurance, real-time auditing, predictive analytics, ethical AI governance, and cybersecurity assurance in enhancing sustainability assurance quality and audit transparency.

Author Contribution

For transparency, we require corresponding authors to provide co-author contributions to the manuscript using the relevant CRediT roles. The [CRediT taxonomy](#) includes 14 different roles describing each contributor's specific contribution to the scholarly output. The roles are: **Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing - original draft; and Writing - review & editing.** Note that not all roles may apply to every manuscript, and authors may have contributed through multiple roles
Dedy Iswanto: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft.

Prima Ayu Novita Junianto: Data curation, Validation, Visualization, Supervision, Writing – review & editing.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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