INTI JOURNAL | Vol.2024:46
eISSN:2600-7320

Artificial Intelligence in Engineering Education: A Review of Pedagogical Innovations

Naixin Zhang[1,2], WaiYie Leong[2*], Tong Zhang[3], Changqing Wei[1]

[1]Chengdu Jincheng College, Chengdu Sichuan 611731, China
[2]INTI International University, Nilai 71800, Malaysia
[3]The Third People's Hospital of Chengdu, The Affiliated Hospital of Southwest Jiaotong University, Chengdu Sichuan 610014, China

[*]**Email:** waiyie@gmail.com

Abstract

This study critically evaluates the integration of artificial intelligence (AI) into engineering education, with a specific focus on its transformative role within the Digital-Intelligent Era. Drawing on General Systems Theory (GST), this research synthesizes insights from 82 empirical studies spanning 2011 to 2024, exploring AI's impact on the evolution of educational frameworks. The study identifies six key application domains of AI within engineering education, including intelligent tutoring systems, adaptive learning platforms, virtual laboratories, and personalized curriculum design. It highlights the synergy between AI and other emerging technologies, such as 5G, Cloud Computing, and Big Data, driving pedagogical innovation and enhancing the learning experience. Additionally, the paper addresses challenges related to the implementation of AI-based educational strategies, including infrastructure limitations, resistance to change, and equity concerns. Finally, it offers strategic solutions to overcome these challenges, fostering a more inclusive and effective educational environment.

Keywords

Intelligent Engineering Education, Artificial Intelligence Integration， Educational Innovation, General Systems Theory, Technological Synergy

Introduction

The international discourse on talent development is converging on comprehensive educational frameworks, underscored by the integration of transformative technologies such as Artificial Intelligence (AI), 5G, the Metaverse, Big Data, Cloud Computing, Blockchain, and ChatGPT. These technologies are reshaping industries and driving profound changes in educational paradigms. In this context, the advent of Industry 5.0 signals a pivotal shift towards the "Digital-Intelligent Era" (Supriya et al., 2024), where technological advancements are intricately linked with societal evolution. This transition, from industrial to intelligent societies (Iatrellis et al., 2023),

Submission: 13 September 2024; **Acceptance:** 29 November 2024

has catalyzed a transformation in productivity, economic structures, and educational models, reflecting the symbiotic relationship between technological innovation and societal development.

A key facet of this transformation is the integration of Artificial Intelligence (AI) into engineering education. AI's potential to revolutionize educational frameworks is evident through its applications in intelligent tutoring systems, adaptive learning platforms, and personalized curriculum design (Huang et al., 2023; Leong, 2024). These AI-driven solutions allow for highly individualized learning experiences that meet diverse student needs, improving both engagement and retention. Furthermore, the integration of 5G and Cloud Computing enhances the capabilities of virtual laboratories and remote learning environments, making high-quality educational resources more accessible to a global student body (Di & Zheng, 2022). AI, when combined with Big Data and Blockchain, further enhances curriculum development, resource allocation, and educational management, providing an integrated approach to educational innovation (Qiao & Fu, 2023).

Engineering education, long rooted in scientific and technological principles, must evolve alongside industrial and societal transformations. The infusion of digital and intelligent technologies is essential for shaping the future trajectory of this field. As we enter the "Digital-Intelligent Era," AI’s role in transforming educational processes—from a tool for content delivery to a collaborative partner in learning—becomes critical. However, challenges remain, such as insufficient technological infrastructure, outdated curricula, and concerns regarding equitable access to these advanced educational technologies. Addressing these challenges requires a strategic, AI-driven approach that not only incorporates technology as a tool but also fosters a more inclusive and efficient educational environment.

This paper explores the transformative role of AI in engineering education, providing a detailed examination of its application across various domains. It underscores the theoretical foundations, practical applications, and challenges of integrating AI, and offers strategies for overcoming barriers to innovation (Rao & Singh, 2020). The focus is on providing actionable insights to promote pedagogical innovation and research in the context of emerging technologies (Leong, Leong, & San Leong, 2024).

In recent years, the integration of Artificial Intelligence (AI) into educational systems has attracted substantial attention, driven by its transformative potential. At the heart of this research is General Systems Theory (GST), an interdisciplinary framework introduced by Ludwig von Bertalanffy in the 1940s, which offers valuable insights into understanding complex systems and their interrelated components (Hofkirchner & Schafranek, 2011). GST posits that systems, regardless of their specific domains, share common principles, and its holistic approach provides an ideal lens for analyzing the integration of intelligent technologies into education. By applying GST to the study of intelligent engineering education, we aim to explore how AI technologies interact with educational components such as curricula, teaching methods, and learning outcomes. This framework enables us to systematically investigate the dynamic relationships between these elements, highlighting the synergy between technological advancements and educational practices.

AI’s role in education can be viewed through the lens of systems theory, where each technological innovation—be it intelligent tutoring systems, adaptive learning platforms, or AI-driven curriculum design—functions as an essential part of the educational system's larger ecosystem. These AI technologies, when integrated thoughtfully, have the potential to enhance the responsiveness of the system to the needs of students, increase personalization, and improve overall learning outcomes. However, challenges remain in fully realizing this potential, particularly in terms of infrastructure limitations and equitable access. GST helps address these challenges by suggesting that successful integration of AI requires a balanced interaction between technology, human factors, and the organizational structure of educational systems (Leong et al., 2023a). Thus, this research builds on GST by exploring how AI-based interventions can foster more adaptive, responsive, and personalized learning environments in the context of engineering education.

Moreover, this paper extends current theoretical discussions by providing empirical evidence on the effectiveness of AI in engineering education, drawing on over 82 studies from 2011 to 2024. By synthesizing these findings, we identify key domains where AI is making a significant impact and offer strategic recommendations for overcoming the barriers to AI integration. Through this approach, we aim to enrich existing theoretical frameworks with insights on how intelligent technologies can drive innovation and improve the effectiveness of education systems.

Methodology

In this scholarly endeavor, we have rigorously adhered to the PRISMA framework for a systematic literature review（See figure 1）(Page et al., 2021), which provides a structured approach to

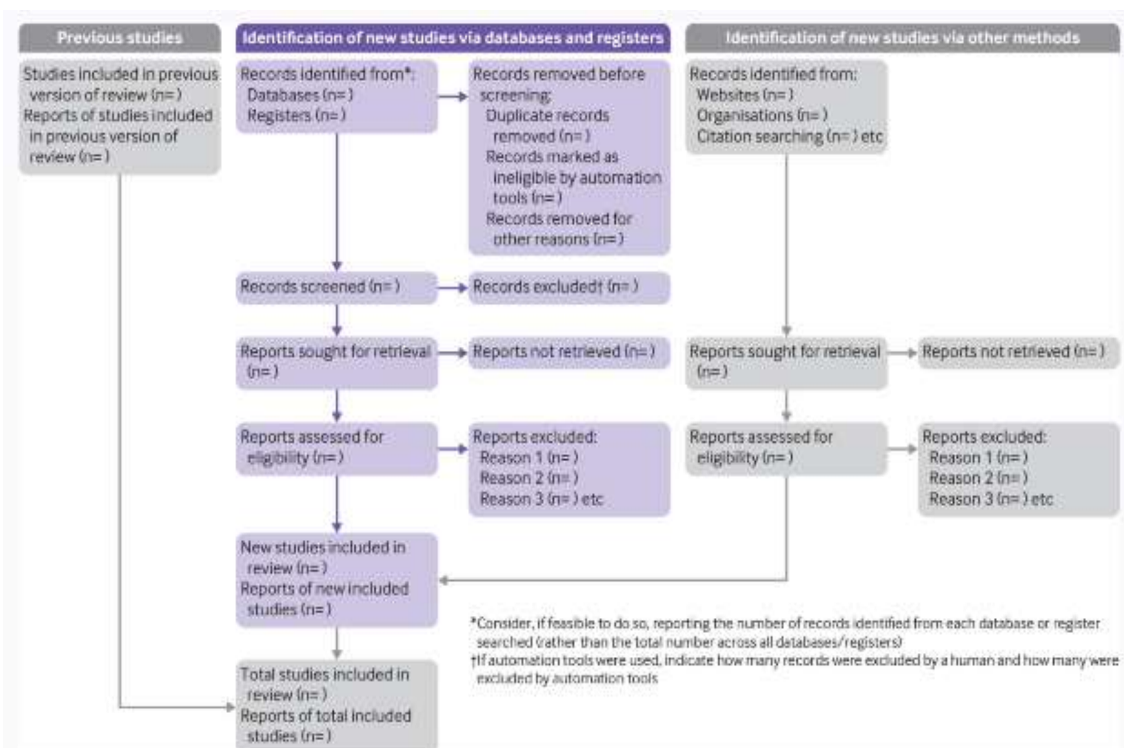

Figure 1. PRISMA 2020 flow diagram template for systematic reviews.(Page et al., 2021)

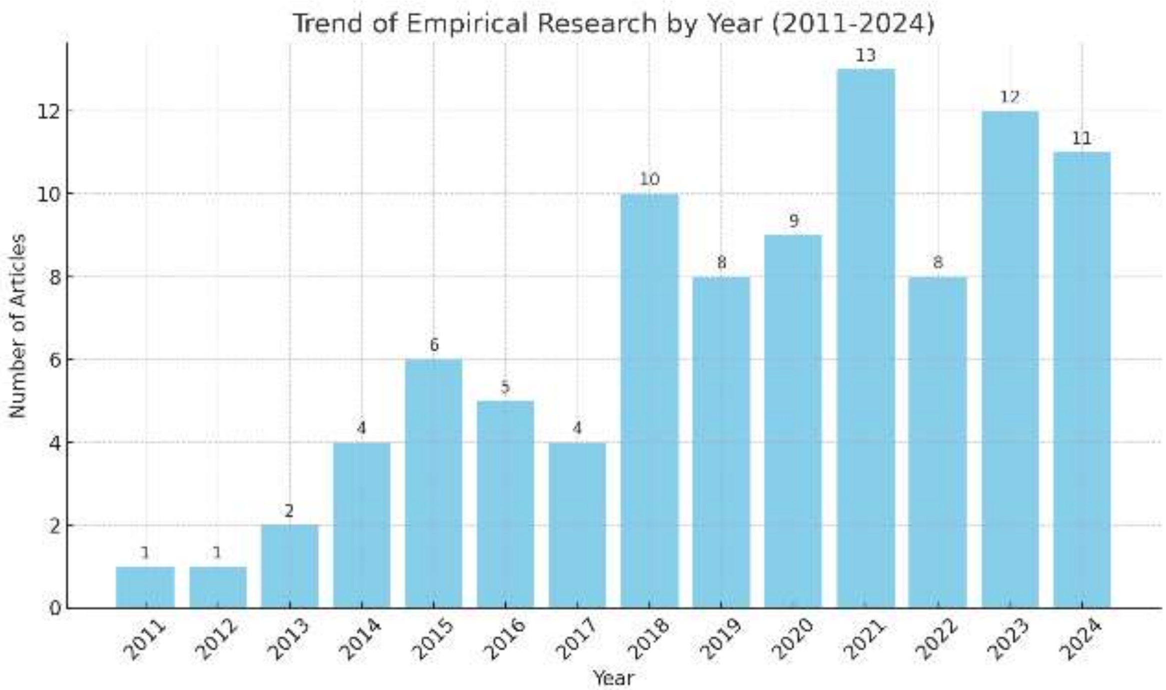

Figure 2. Trend of by Year (2011-2024)

synthesizing evidence-based findings. Our initial search encompassed authoritative databases, including Web of Science, Scopus, IEEE Xplore, and Google Scholar, yielding a collection of 4,385 articles. Subsequent deduplication efforts resulted in a refined set of 3,872 unique articles. To this corpus, we added an additional 300 articles from alternative sources, totaling 4,172 records for consideration. A meticulous screening of titles and abstracts followed, culminating in the selection of 82 articles for systematic evaluation.

Guided by the theoretical underpinnings of General Systems Theory (GST), introduced by biologist Ludwig von Bertalanffy in the 1940s (Hofkirchner & Schafranek, 2011), this interdisciplinary framework is designed to identify commonalities among various systems and to establish universal principles for their analysis and description. GST offers a comprehensive methodology for examining complex systems, particularly suitable for understanding the integration of intelligent technologies within educational systems. By applying GST to the study of intelligent engineering education, this research aims to systematically investigate the interplay between AI technologies and educational elements and to assess how these interactions influence the overall effectiveness of the educational system(Leong et al., 2023a).We conducted a thematic analysis to delve into the complex interrelationships between intelligent technologies and multiple facets of engineering education.

Results and Discussion

The Connotation of Intelligent Engineering Education. Our research revealed a consistent upward trend in empirical studies on intelligent engineering education from 2011 to 2024 (Figure 2). This trend indicates an increasing focus on the integration of AI into engineering education, particularly in recent years. A rigorous systematic review, following the PRISMA framework, narrowed 4,172 records to 82 high-quality peer-reviewed articles, reflecting the latest advancements in the field. The review found that intelligent tutoring systems (ITS) and automated assessment technologies are among the most widely discussed tools in the field (Rao & Singh, 2020). This aligns with the growing emphasis on AI applications in engineering education, signaling the need for further integration of such technologies to enhance the learning process. Table 1 presents the disaggregated statistical data on the most discussed application categories in intelligent engineering education.

Table 1. Disaggregated statistical data

Serial	Application category	Number of Articles	Proportion （%）
1	Intelligent Tutoring Systems	23	28.6
2	Automated Assessment	21	25.4
3	Virtual Laboratories	17	20.6
4	Learning Behavior Analytics	10	12.7
5	Personalized Learning Paths	8	9.5
6	Educational Robots	3	3.2

Integrating Intelligent Technologies in Engineering Curricula. All 82 studies reviewed emphasize the significance of integrating intelligent technologies, especially in STEM and interdisciplinary fields. This integration not only enhances the learning environment but also creates more personalized, adaptive educational experiences. The trend is shifting toward more sophisticated teaching methods that incorporate AI to meet the diverse needs of students (Welsen, 2024). This finding confirms the importance of AI in creating flexible and effective curricula.

Teaching Strategies in the Intelligentization of Engineering Education. The studies identified nine key characteristics that define the intelligentization of engineering education. These include the use of intelligent tutoring systems, learning behavior analysis, and automated assessments. The results suggest that a combination of these technologies, rather than reliance on a single tool, leads to more effective teaching outcomes (Vantard et al., 2023; Welsen, 2024). This finding points to the need for integrated technological solutions in education, as opposed to fragmented implementations.

Students in the Intelligentization of Engineering Education. The majority of studies identified higher education institutions as the primary setting for AI applications, with university-level education being the most common. The analysis revealed that larger sample sizes were typically found in higher education, suggesting that intelligent technologies are particularly effective at this stage (Welsen, 2024). This finding emphasizes the role of AI in improving the learning experiences of students at advanced educational levels.

The Role of Educational Media in Intelligent Engineering Education. Educational media, especially intelligent tutoring systems and automated assessments, were central to the findings. Most of the reviewed studies (79 out of 82) focused on the use of educational media such as online platforms and mobile tools. The results highlight the crucial role of these tools in facilitating learning in intelligent engineering education (Tapalova & Zhiyenbayeva, 2022). This aligns with the growing importance of digital learning environments in modern education.

The Educational Environment in Intelligent Engineering Education. The educational environment was identified as a key factor in the intelligentization of engineering education. The results indicated that most studies emphasized traditional face-to-face learning environments, while others pointed to the rising significance of web-based and AR/VR learning spaces. The integration of these diverse learning environments, supported by intelligent technologies, shows the adaptability of modern educational settings (Leong et al., 2023b). This finding emphasizes the transformative potential of AI in creating more dynamic, flexible learning environments.

Challenges in the Intelligentization of Engineering Education. Despite the potential of AI technologies, our findings highlight significant challenges, including infrastructure limitations, resistance to change, and outdated curricula (Cheung et al., 2021). These obstacles must be addressed for the successful implementation of AI in engineering education. The study stresses the importance of strategic planning, professional development, and infrastructure investment to overcome these barriers.

Overcoming Barriers and Facilitating Technological Adoption. Overcoming inertia within educational systems is critical for the successful integration of intelligent technologies. The results suggest that resistance to change and lack of proper teacher training are major barriers to adoption. To facilitate the integration of AI, it is necessary to adopt a comprehensive approach that includes both technological advancements and support systems for educators (Supriya et al., 2024). This highlights the importance of preparing educators for the evolving landscape of AI in education.

Conclusions

This study underscores the importance of intelligent engineering education as a transformative force in modernizing educational practices for the "digital-intelligence era" (Acosta Castellanos & Queiruga-Dios, 2021). By strategically incorporating advanced digital technologies like the Internet of Things (IoT), cloud computing, and artificial intelligence (AI), the research advocates for a redefined educational landscape that fosters both academic and industrial synergies. The ultimate goal is to establish an interactive, student-centered educational system that prepares engineers for the future. Figure 3, which illustrates the integration of these technologies, serves as the overarching framework for this study, encapsulating the interconnectedness of the key elements of intelligent engineering education. Importantly, this study highlights how the integration of these technologies is not just about enhancing educational processes but also about facilitating a paradigm shift toward a more dynamic, adaptable educational framework. In this context, AI plays a pivotal role, driving not only the deeper integration of technology in educational activities but also fostering substantial changes in the way education is delivered.

The core features of intelligent engineering education, as identified in this study, include technological cluster coupling, resource diversity integration, platform-integrated intelligence, and human-machine collaborative interaction (Lorna et al., 2024). These features collectively constitute the backbone of intelligent engineering education, with AI acting as a crucial catalyst. Figure 3 effectively visualizes this conceptual architecture, showing how these features interconnect and operate together within the system. The integration of machine learning and data mining facilitates the seamless coupling of diverse educational technologies, creating a more interactive and resource-efficient system (Mayilyan, 2024). Furthermore, AI-driven adaptive learning platforms personalize the educational experience, offering students tailored learning paths that enhance their engagement and knowledge retention.

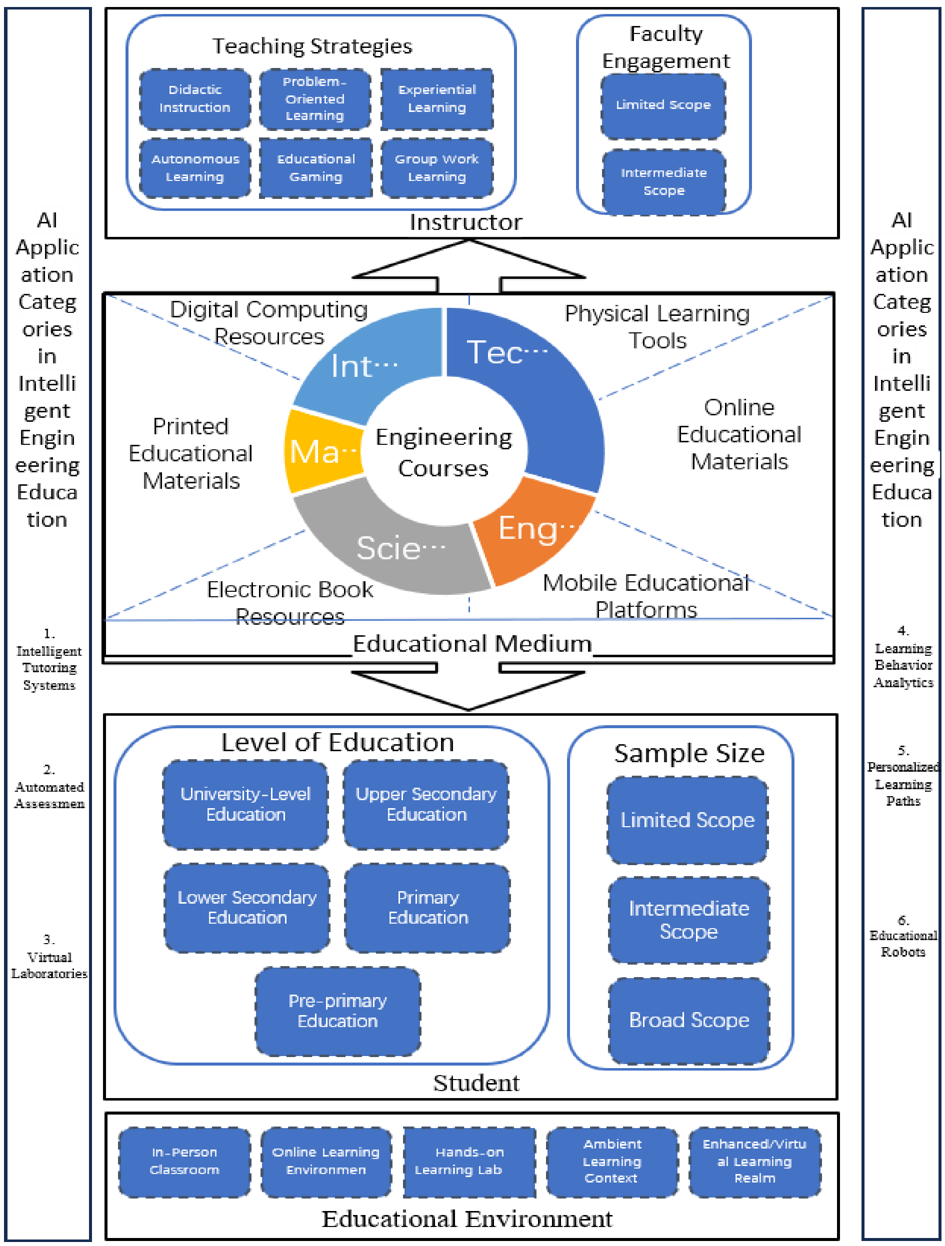

Figure 3. Engineering Intelligent System

Another significant contribution of AI in intelligent engineering education is its ability to enhance human-machine interaction, providing real-time feedback to both students and instructors. This fosters a more responsive and effective learning environment. AI also supports personalized learning by analyzing students' behavior and adapting the educational content to meet their individual needs (Najam, 2023). This adaptability not only increases learning efficiency but also ensures that education is more inclusive, catering to diverse learning styles and paces. The interconnected features illustrated in Figure 3 emphasize how AI enables personalized learning and enhances interaction between students, instructors, and the system, thus contributing to a more dynamic educational experience.

The integration of AI with other emerging technologies such as virtual reality (VR) also significantly enriches the educational experience. This combination enables a seamless integration of virtual and real-world scenarios, providing students with practical learning environments that closely simulate industry practices. By combining virtual and physical learning spaces, AI-driven platforms promote hands-on experience that is crucial for developing practical engineering skills. Moreover, AI's data-driven approach allows for continuous evaluation, offering students and educators valuable insights into learning progress, which contributes to more precise and effective teaching strategies. Figure 3 demonstrates how AI and VR work in tandem to create immersive learning experiences that are aligned with real-world engineering challenges.

This research highlights not only the potential of AI in transforming engineering education but also its broader implications for educational policy and practice. By offering a comprehensive framework, this study suggests that AI technologies can facilitate a more personalized, efficient, and inclusive education system. These insights are not only relevant for academic institutions but also for policymakers aiming to adapt educational systems to the demands of the digital age. Future research should continue to explore how AI can be further integrated into the curriculum to enhance its effectiveness, addressing potential challenges related to infrastructure, resistance to change, and the need for professional development in the field. Figure 3 captures the comprehensive integration of AI across various educational dimensions, providing a clear roadmap for the future of intelligent engineering education.

Acknowledgments

We would like to express our sincere gratitude to INTI International University, Chengdu Jincheng College, and Professor Ir. Dr. Leong Wai Yie for their invaluable support throughout this research. Special thanks also go to the organizers of ICETSD 2024. We deeply appreciate the guidance provided by the Department of Engineering Education, as well as the feedback from the peer reviewers, which greatly enhanced the quality of this paper.

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