Front. Digit. Educ., 2024, 1(4): 279–294
https://doi.org/10.1007/s44366-024-0031-x

RESEARCH ARTICLE

Digital Pedagogy for Sustainable Education Transformation: Enhancing Learner-Centred Learning in the Digital Era

Ronghuai Huang, Michael Agyemang Adarkwah, Mengyu Liu, Ying Hu, Rongxia Zhuang, Tingwen Chang
Smart Learning Institute, Beijing Normal University, Beijing 100082, China

Abstract Higher education systems are under increasing pressure to embrace technology-enhanced learning as a meaningful step towards the digital transformation of education. Digital technologies in education promise optimal teaching and learning, but at the same time, they put a strain on education systems to adapt pedagogical strategies. Classical pedagogical frameworks such as Dewey, Piaget, and Vygotsky's theories focused on student agency and are not specific to contemporary education with ubiquitous digital technologies. Hence, there is a need for a novel and innovative pedagogical framework that aligns with these emerging and advanced digital technologies. However, recent guidelines to incorporate emerging digital technologies in education have largely focused on ethical dimensions and assessment practices. The lack of an overarching pedagogical framework for teaching and learning practices in the digital era is a threat to quality education. The current study proposes a digital pedagogy for sustainable educational transformation (DP4SET) framework applicable to the new modes of teaching and learning powered by digital technologies. The DP4SET framework comprises four components that advocate for digital competence for accessing deep learning, evidence-based practice with quality digital resources, learning environments with applicable digital technology, and synergy between human teachers and trustworthy artificial intelligence (AI). A real-world application of the DP4SET framework in Chinese contexts proves that it promotes the effective use of technology and significantly reshapes teaching and learning in and beyond the classroom. The proposed digital pedagogy framework provides a foundation for modern education systems to accommodate advanced digital technologies for sustainable digital transformation of education.

Keywords digital pedagogy, innovative pedagogy, digital transformation, technology-enhanced learning (TEL), artificial intelligence (AI)

Received July 8, 2024; revised September 28, 2024; accepted November 6, 2024
Michael Agyemang Adarkwah (✉)
E-mail: adarkwahmichael1@gmail.com

1 Introduction

In recent times, technological innovations quickly become obsolete as soon as they are invented. A variety of digital technologies have been manufactured at an exponential rate for use across diverse sectors such as education. It is believed that technology use in education will expedite the digital transformation of education (McCarthy et al., 2023; Timotheou et al., 2023). Digital transformation of education involves the "use of digital innovation in expanding access to educational opportunities and advancing inclusion, enhancing relevance and quality of learning, building information and communication technology (ICT)-enhanced lifelong learning pathways, strengthening education and learning management systems, and monitoring learning processes" (UNESCO, 2023a). Digital transformation is considered a vehicle to accomplish the Education 2030 agenda, facilitate its widespread adoption, and achieve the Sustainable Development Goals (SDGs) (Trevisan et al., 2024). According to Hashim et al. (2022), achieving sustainable futures of education for global higher education hinges on the digital transformation of education.

Although an important step, the call for transforming education using digital technologies has placed higher education institutions (HEIs) under increasing pressure to embrace technology-enhanced learning (TEL). COVID-19 further popularised TEL even for educational institutions in different countries that were unaccustomed to technology use in education (Nurhas et al., 2022). During the United Nations (UN) Transforming Education Summit 2022, where the utilisation of digital technologies is presented as a solution to the global education emergency regarding

inclusivity, equity, quality, and sustainability (UN, 2023). As a result, digital technologies have unsurprisingly become a crucial aspect of teaching and learning in contemporary education systems. High-quality content, capacity to use digital technology, and digital connectivity are emphasised as instrumental in unlocking the potential of digital learning.

Consequently, educational institutions are required to keep up with the fast pace of the use of digital technologies for teaching and learning. One such vital component of all educational systems is pedagogical strategies that guide teaching and learning practices. Nonetheless, despite the prevalence of technological innovation and new pedagogies, education outcomes are often less than expected or promised (McCarthy et al., 2023). For example, although classical pedagogical framework such as Vygotsky's pedagogical theory (Daniels, 2001) may improve an aspect of teaching and learning, it may not be designed specifically to align with newly advanced technologies such as artificial intelligence (AI) or generative artificial intelligence (GenAI). In order to achieve successful digital transformation of education, it is necessary to have clear guidelines on how to diffuse digital technologies for educational purposes. An effective digital strategy for implementing technology in education needs to be created for educators.

Current digital pedagogies may be ineffective in some learning settings infused with technology. For example, Redecker (2017) found the technological pedagogical content knowledge (TPACK) framework by as more teacher-centred and sought a more learner-centred approach by developing the digital competence of educators (DigCompEdu). The DigCompEdu highlighted the importance of digital competencies in teaching and learning. However, the framework focused more on educators' digital competencies. After reviewing several publications on digital pedagogy, a digital pedagogy model for education was developed. However, Väätäjä and Ruokamo (2021) acknowledged that their digital pedagogy model needed additional assessment and enhancement to better assist educators in integrating digital technologies into their teaching practices. That is, there is little evidence of its real-world application in TEL environments.

In response, the conceptual study aims at developing a digital pedagogy framework for HEIs needed for the sustainable transformation of teaching and learning in the digital era. This is one of the few studies to propose an innovative digital pedagogy that considers new modern and advanced technologies such as GenAI in education. Based on the UNESCO (2023b) call to promote a "human-centred and pedagogically appropriate interaction" approach in education, the newly proposed digital pedagogy framework aims to foster human–machine collaboration and interaction by actively using digital technology for learning. We believe that the learner-centred pedagogy proposed in this study will serve as a roadmap for designing TEL in the AI era. Therefore, the following overarching research question guides the study.

(1) What digital pedagogy framework effectively integrates emerging technologies to enhance teaching and learning in contemporary education institutions?

To address this research question, we conduct the following steps: Firstly, we acknowledge the existence and shortcomings of the renowned pedagogy framework TPACK and establish how it differs from the digital pedagogy framework. Secondly, we explore the debatable role of technology in education and call for a clear innovative digital pedagogy framework for education. Thirdly, we propose the construction of smart education system as a condition for implementing the digital pedagogy framework to foster deep learning. Fourthly, we discuss the key concerns of effective teaching to achieve deep learning in educational institutions. Fifthly, we provide a case study in China based on digital assessment during COVID-19 as an example of a real-world application of the digital pedagogy framework. Sixthly, we propose an innovative digital pedagogy framework and conclude with implications for educational policy and practice.

2 TPACK and Digital Pedagogy

The TPACK framework divides the teacher's knowledge into three parts, including content knowledge, pedagogical knowledge, and technological knowledge (Koehler & Mishra, 2009). The TPACK model shows what kind of knowledge teachers need. It emphasises the importance of teachers using technology tools in class and integrating content knowledge, pedagogical knowledge, and technological knowledge. However, it is difficult for teachers to differentiate the concepts of these three kinds of knowledge within the TPACK model. Moreover, the TPACK model only focuses on teacher's knowledge but lacks attention and understanding of how classroom instruction should be implemented and how it affects student learning.

Researchers have criticised TPACK for effective technology integration to reimagine new modes of learning (Cavanagh & Koehler, 2013; Pamuk, 2012; Swallow & Olofson, 2017). TPACK has a pedagogical component but there are confusion and contradictions regarding the use of TPACK highlighting its complexity for effective adoption of technology (Cavanagh & Koehler, 2013). According to Pamuk (2012), educators experience difficulty in explaining interactions among knowledge bases of the TPACK framework. While

TPACK has potential to offer valuable insights for educators regarding the integration of technology into teaching and learning, this potential is not always clearly articulated within the framework. The current representation suggests that TPACK knowledge consists of various knowledge bases, but it fails to outline the sequential steps necessary for developing a TPACK knowledge base. The lack of a common understanding between the particular context, knowledge development, and instruction (Swallow & Olofson, 2017) makes it difficult to implement TPACK in diverse educational settings.

Additionally, Cavanagh and Koehler (2013) state that there are concerns about potential constraints to using the TPACK framework by researchers in terms of logistics, resource issues, or methodological exigencies and call for improvement of TPACK measurements. Due to the complexities of TPACK and the lack of focus on understanding how it could facilitate technology adoption for effective teaching and learning, Saubern et al. (2020) in their research opened up discussions on the need to reboot applications of TPACK. In their study, Saubern et al. (2020) mentioned that after 15 years and over 3,000 publications on TPACK, there was still little knowledge about what it entailed, and they raised fundamental questions involving how to measure TPACK, how to teach it, and how to use it to make teaching with technology effective. Recent criticisms of TPACK involve imprecise descriptions of knowledge domains, lack of usefulness in practice, and ignorance of context (Pareto & Willermark, 2019). Pareto and Willermark (2019) mentioned that the technology domain of the TPACK framework in particular had been criticised for being vague and extensive with difficulty in distinguishing different knowledge domains making it not practically useful.

The digital pedagogy for sustainable educational transformation (DP4SET) framework offers a simple approach to integrating technology in education for effective teaching and learning in contrast to the complexities highlighted in the TPACK framework by several scholars. At the same time, its applicability is pertinent to new modes of teaching and learning driven by newly advanced AI technologies that are ubiquitous in the digital era. Additionally, unlike the TPACK framework which places more emphasis on teachers, the DP4SET framework advocates for a student-centred approach to integrating technology to enhance teaching and learning practices (Shehata et al., 2023). The DP4SET framework expands upon or diverges from the traditional TPACK framework to meet diverse demands of modern digital education. TPACK primarily focuses on how teachers integrate technology, content, and pedagogy to enhance classroom effectiveness. TPACK's structure may lack adaptability when addressing emerging digital pedagogies, particularly in the flexible application of digital tools. In contrast, DP4SET is designed with contemporary digital education needs, aiming at accommodating rapidly evolving educational technology and diverse teaching environments. DP4SET, with the fusion of a student-centred approach, enhances flexibility and adaptability, aligning it with the trends in modern educational transformation.

With the gradual deepening of digital transformation of education, it has become an inevitable trend for digital technology to deeply integrate into teaching and to change the way of teaching and learning. The increased use of technology in education creates a challenge of how best to utilise technology for different purposes to maximise learning, and it is argued that unless there is an emphasis on introducing digital pedagogies in teaching, there is not going to be a big change in education.

Digital pedagogy refers to a teaching method that emphasises the transformation of teaching and learning throughout the entire classroom process, empowered by digital technology. It not only focuses on teachers' knowledge and abilities to engage in digital instruction, but also focuses on students' capabilities to use technology for communication, collaboration, construction, exploration, and management. The main initiative for the adoption of new technologies should be created by pedagogical needs that could not be applied without technology. Based on the concept of experiential learning, the key to learning lies in students' active exploration and practice within real-world contexts (Dewey, 1938). Digital technology enables this possibility, allowing students to deepen their understandings through interaction, construction, and feedback. Through digital pedagogy, students are not merely recipients of information but participants in the generation of knowledge. According to Piaget's theory of cognitive development, students' cognitive abilities differ across stages (Piaget, 1970). Digital pedagogy offers diverse tools that help students engage in personalised learning based on their cognitive levels, making learning more targeted and effective. This approach supports students in developing understandings and skills appropriate to their cognitive stages, thereby promoting continuous growth.

Vygotsky's social constructivist theory further reinforces the significance of digital pedagogy (Vygotsky, 1978). He argued that knowledge was constructed through social interactions, and technology provides ample opportunities for students to collaborate. With digital pedagogy, students can not only share knowledge resources with teachers and peers but also co-construct understanding through collaboration, and achieve breakthroughs within their zone of proximal development. This approach focuses on teachers' digital teaching knowledge and skills,

emphasises on students' self-management capability with technology, and foster a more autonomous exploration and construction of knowledge. Developing digital pedagogies as a way of reframing pedagogies to better meet the needs of current and future students is an imperative in a digital world.

Overall, digital pedagogy has changed the way people acquire, interact with, and process knowledge, making participation in generation and construction of knowledge more significant than the knowledge itself. Therefore, the introduction of digital pedagogy shifts the focus of teaching from the teacher's knowledge and skills to different ways of working in the digital world. It transforms the emphasis on teachers' literacy and ability to effectively organise and manage instruction with digital technology, and on students' using technology to facilitate and manage their own learning. At the same time, it emphasises evidence-based, continuous improvement in teaching and deep learning. By integrating experiential learning, cognitive development, and social constructivism, digital pedagogy drives a shift in teaching focus, redirecting the classroom's attention from knowledge transmission to technology-enabled learning experiences and skills development, and aligning with the need for profound educational transformation in the digital era. In the next section, we provide the debatable role of technology in education and the need to have an innovative digital pedagogy framework for education.

3 Debate on Learning Technology during Digital Transformation

While technology holds a transformative potential in adding value to education, at the same time, it poses a danger to achieving quality education. For example, scores of evidence exist regarding technology providing education lifelines for millions but excluding many more during the COVID-19 pandemic (Adarkwah, 2021; Nurhas et al., 2022; UNESCO, 2023a). In this light, the *2023 Global Education Monitoring Report* (2023 GEM Report) issued an urgent call for education systems to define technology in their own terms when incorporating it into pedagogical process (UNESCO, 2023c). Moreover, this call to action also exposed the practical and ethical dilemmas faced by institutions.

One of the most pressing challenges is the digital divide, where accessing to necessary technology and digital literacy is unevenly distributed, particularly in low-income regions. This exacerbates educational inequalities, as students in under-resourced communities may lack infrastructure or skills to access digital learning platforms (UNESCO, 2023a). Some of the inequalities perpetuated by technology use in education are due to the digital divide in developing economies that is further exacerbated by crises such as the COVID-19 pandemic (Adarkwah, 2021). Additionally, reliance on technology in education raises significant ethical concerns, such as data privacy, surveillance, and commercialisation by technology companies (Zuboff, 2019). These issues pose a risk to student autonomy and highlight a clear regulatory frameworks to protect vulnerable populations.

Ethical considerations also extend to the use of GenAI in educational settings. Utilising GenAI tools comes with risks and errors (Hacker et al., 2023). Some of the risks involve discrimination, privacy concerns, disrespectful responses (Hacker et al., 2023), misleading and biases (Tlili et al., 2023), and copyright concerns (Stokel-Walker & Noorden, 2023). GenAI tools like ChatGPT can also reduce critical thinking ability of learners (Sallam et al., 2023; Yu, 2023).

As large language models like ChatGPT and Google Bard become more prevalent, questions arise regarding academic integrity and potential for these tools to cause cheating (Kasneci et al., 2023). Susnjak (2022) raised the similar question of whether ChatGPT might signal the end of academic integrity. Moreover, ChatGPT is able to exhibit critical thinking and generate highly realistic prompts with minimal input which poses a threat to academic integrity, particularly in online exams in tertiary institutions. The banning of such tools by institutions like the New York City Department of Education reflects growing concerns about the appropriate use of AI in education. Teachers are expected to address some of the challenges, especially those relating to academic integrity by employing traditional forms of assessment, such as oral examinations and the use of AI detectors.

Integrating AI in pedagogy necessitates a shift in the role of teachers, from knowledge transmitters to facilitators of critical thinking, while ensuring that AI complements rather than replaces human instruction. These ethical challenges demand robust digital literacy programs that equip both students and educators to navigate AI responsibly. It is evident that HEIs and other educational institutions need a new mode of teaching and learning facilitated by appropriate digital technologies. Technology is always transitioning and education systems must co-evolve with it.

In light of these concerns, the implementation of digital pedagogy must be cautious. Practical challenges, such as continuous evolution of technology, require educational institutions to not only keep up with technological advancements but also invest in teacher training and support systems to ensure effective usage (Pettersson, 2018). Without professional training and infrastructure, the promise of TEL may remain unfulfilled, as learners may reject or misuse new tools (Mehta et al., 2019). Additionally, the overreliance on

technology can detract from development of interpersonal skills and face-to-face interactions, which remain crucial components of holistic education.

As educational implications of such technologies are unfolding, developing an innovative digital pedagogy for sustainable education transformation is imperative for education systems. Digital pedagogy describes how to teach using digital technologies (Pettersson, 2018), and is defined as "the art of teaching, computer-driven digital technologies, which enrich learning, teaching, assessment, and the whole curriculum" (Kivunja, 2013). Digital pedagogy for the sustainable transformation of teaching and learning is needed for the following three reasons: the need for a resilient pedagogy as part of a crisis-resistant framework for education in response to COVID-19 disruption of education, the unsuccessful implementation of TEL despite massive investment in technology, and the advent of GenAI such as ChatGPT, Google Bard, and Claude.

First, building back education after the huge blow from the COVID-19 pandemic demands the need for establishing resilient education systems championed by an innovative digital pedagogy. Disaster is a catalyst to transform the status quo of education (Morris et al., 2022; Zancajo et al., 2022), in order to build the digital resilience of students in the post-COVID world. Digital resilience emphasises possessing digital literacy to navigate digital contexts and self-efficacy to tackle digital problems (Lee & Hancock, 2023), and a "resilient pedagogy" for teachers to creatively adapt to new situations (Chow et al., 2020). Education in the post-COVID world should be built around open-source technologies within the pedagogical space (UNESCO, 2020).

Second, despite significant investment in digital technology in education, learning technologies need to be better adopted for instruction, for learners might discontinue or reject new technology (Mehta et al., 2019). Hence, developing an innovative digital pedagogy to build students' interest in learning is significant for providing lifelong opportunities in education. An innovative digital pedagogy is more than a simple use of technology for learning but one that promotes independent learning, problem-solving, and high-order thinking skills (Väätäjä & Ruokamo, 2021). Digital pedagogy that emphasises adopting a learner-centred approach when implementing digital technologies in education is crucial in this digital age (Shehata et al., 2023).

The inception of GenAI technologies such as ChatGPT has sparked conversations about their pedagogical appropriateness in education. In response, some educational institutions, such as New York City Department of Education, banned ChatGPT from school devices and networks because of the possibility of cheating (Kasneci et al., 2023). Tlili et al. (2023) advocated for a new teaching philosophy on integrating GenAI into education. A novel digital pedagogy which takes into account the changes that the AI revolution is bringing into education, can help achieve SDGs. What role will teachers play amid the rapid growth of AI technologies? What will assessment look like in this era where AI can successfully answer exam questions (UNESCO, 2023b)? These crucial questions demand that educators rethink their pedagogies. Moreover, institutions must consider ethical aspects such as ensuring fairness, preventing cheating, and promoting transparency in AI-assisted learning process. There is a need for a digital pedagogy that develops GenAI-related literacy of learners and builds the capacity of teachers and researchers to adequately use GenAI (UNESCO, 2024). We propose that an innovative digital pedagogy will promote deep learning in TEL contexts. To achieve this goal, educational institutions need to embrace a smart education framework (UNESCO IITE et al., 2022).

4 Deep Learning in TEL Contexts

As a condition for implementing a digital pedagogy in TEL contexts to promote deep learning, we propose that modern educational institutions should construct a smart education system built upon three layers, including smart learning environments, technology-enhanced learning and teaching, and evidence-based governance. The smart education system is expected to possess two main features, including performative and constructive feature as shown in Figure 1 (UNESCO IITE et al., 2022). The performative aspect spotlights learner-centred teaching, comprehensive assessment, smart learning environments, continuous improvement, and inclusivity. Constructive facets focus on fostering social learning communities, supporting educators, ethical technology adoption, sustainable reform, and effective collaboration.

Smart learning environments demand the following three items, including effectiveness of learning, efficiency of schooling, and efficacy of digital tools and resources. First, effectiveness of learning means leveraging digital tools and resources to optimise learning process, facilitating deeper understanding, critical thinking, and knowledge retention. Second, efficiency of schooling emphasises streamlining administrative tasks, communication channels, and resource allocation through technology, maximising operational efficiency, and enabling educators to focus more on instructional activities. Third, efficacy of digital tools and resources ensures that technology integrated into learning environment is purposeful and

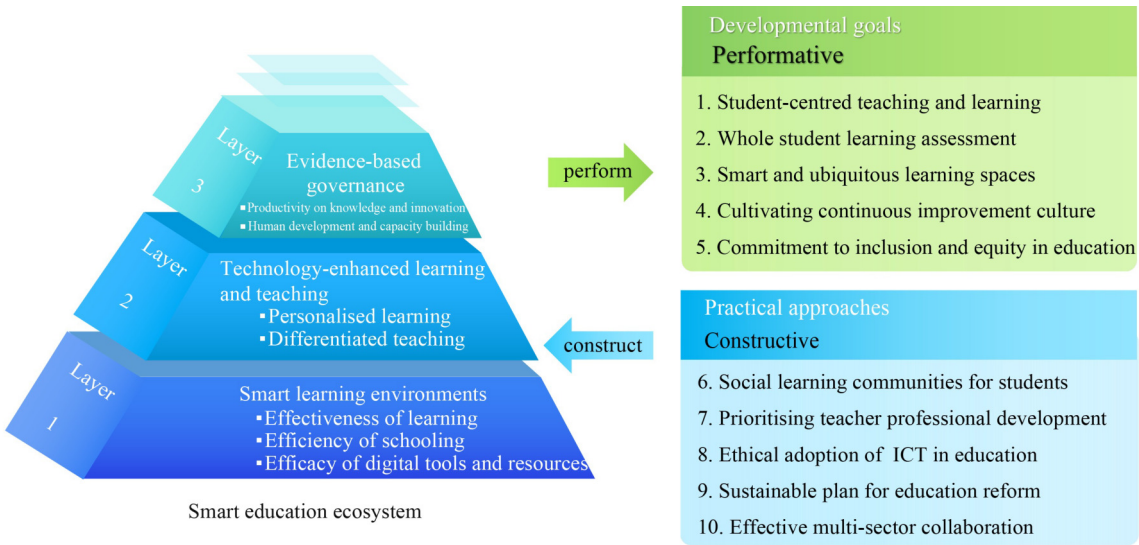

Figure 1 Three layers of the smart education system for modern education. ICT: information and communication technology.

reliable, and supports learning objectives to enhance overall educational experience.

Technology-enhanced learning and teaching call for the following two actions, including personalised learning and differentiated teaching. Personalised learning requires educators to harness technology to tailor educational experiences and contents to individual learners' unique needs and preferences, promoting their engagement and achievement. Differentiated teaching demands educators to utilise technology to facilitate varied instructional approaches and adapt teaching methods to address students' diverse learning styles and levels.

Evidence-based governance focuses on two points, including productivity on knowledge and innovation, and human development and capacity building. Productivity on knowledge and innovation emphasises the importance of research and evidence-based practices to drive knowledge creation. Human development and capacity building nurtures the growth and development of individuals through strategic initiatives that enhance their capabilities and literacies.

Constructing a smart education system serves as a foundation for implementing a digital pedagogy to promote deep learning in TEL contexts for modern education systems. By deep learning, students can pay attention to the underlying meaning of course materials and experiences by using analytic skills, cross-referencing, imaginative reconstruction, and independent thinking (Warburton, 2003). In contrast to deep learning, superficial learning emphasises a simple description of course contents more. Teachers often face with the challenge of motivating learners to seek a deeper understanding during learning process (UNESCO IIEP, 2023). Hence, there is a need to leverage digital technologies in TEL contexts for deeper learning.

Undoubtedly, integrating digital technologies in TEL facilitates the transition from superficial learning to deep learning (Wu, 2023). Technological infrastructure makes it easier for teachers to foster deep learning (Dede, 2014). Employing digital technologies for digital learning in TEL contexts delivers a deeper context, a broader viewpoint, and more stimulating activities than conventional teaching methods (Haleem et al., 2022). Dede (2014) proposed that embracing technologies for TEL was essential because relying on the traditional or labour-intensive education model could be unsustainable in terms of cost and productivity. Moreover, teachers will experience difficulty in promoting deep learning without digital technologies because of the changing students' needs. A new model of teaching and learning in digital contexts encouraging self-directed and deep learning is urgent and paramount in the age of AI (UNESCO IIEP, 2023).

5 Key Concerns of Effective Teaching for Deep Learning

The end goal of an innovative digital pedagogy framework is to promote effective teaching and learning. To bring out the key tenets of what constitutes effective teaching and learning, we reference seminal and relevant literature in the form of a discussion. Our investigation reveals that effective learning and teaching is composed of seven key elements categorised under four main ideas. As shown in the Figure 2, the seven key elements include educational beliefs and focus, delivery and facilitation approach, structuring teaching and assessment, learning activities and feedback, learning strategies and involvement, learning space and expected

mode, and instruction media and digital tools. The four main ideas denote concepts, teachers, students, and environments.

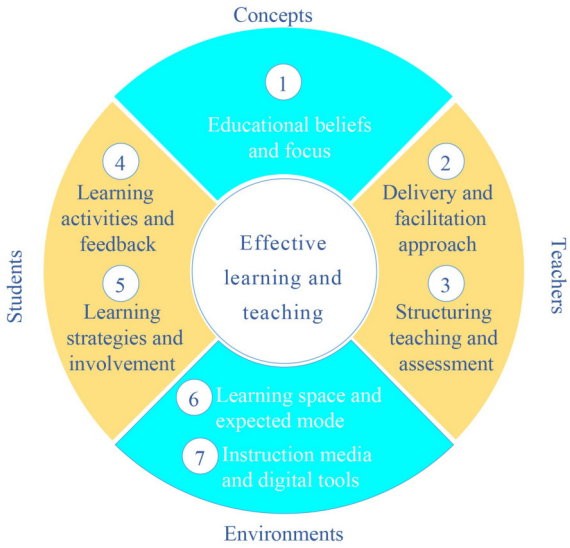

Figure 2 Seven key elements and four main ideas of effective learning and teaching.

The first main dimension of the digital pedagogy framework is the concept. Effective learning and teaching have to be driven by educational beliefs and focus. The educational beliefs and focus of effective learning and teaching suggest that teaching is not merely transferring information but better engaging learners (Gurney, 2007). According to Gurney (2007), the teachers' interaction with learners in class highlights mutual respect and acknowledges the learning process. Teachers create opportunities and experiences for students to engage in exploration and experimentation in a climate that recognises learning as the measurement of acquisition rather than the repetition of right answers (Stipek, 1996). Quality teaching provides a sufficient and effective opportunity to learn (Alton-Lee, 2003).

The second aspect denotes teachers. Teachers play key roles in effective teaching and learning, and they are responsible for adopting the right delivery and facilitation approach and for structuring teaching and assessment. Regarding the delivery and facilitation approach, meaningful subject knowledge is an essential prerequisite for good teaching. Teachers are expected to deliver well-structured lessons and create thought-provoking questions to engage learners (Mourshed & Barber, 2007). Concerning structuring teaching and assessment, Mourshed and Barber (2007) revealed that an effective assessment was a vital ingredient in good teaching. Teachers should possess lesson planning and assessing competence (Krepf & König, 2023).

The third facet of effective teaching is centred on students, and it involves learning activities and feedback, as well as learning strategies and involvement. Teachers design learning activities and provide constructive feedback, and they are responsible for designing learning strategies and creating space to involve students in the learning process. Regarding learning activities and feedback, Ko and Sammons (2013) mentioned that learning activities should be planned to promote good interactions through direct teaching, especially in a group or paired work. Students should have maximum contact with teachers and benefit from teaching and interaction. Muijs and Reynolds (2000) proposed that an interactive plenary session was essential for reviewing, reflecting, consolidating, and representing to check all students' understanding. Regarding learner strategies and involvement, Alton-Lee (2003) called for a pedagogy that promoted learning orientations, student self-regulation, metacognitive strategies, and thoughtful students' discourse. Learning involvement emphasises equitable participation of all students, regardless of their backgrounds, abilities, or learning styles, with the opportunity to engage meaningfully in the learning process. This aims at creating an inclusive learning environment where all voices can be heard, and learners can be encouraged to participate without fear of bias or exclusion.

The fourth aspect is the teaching and learning environment that comprises learning space and expected mode, and instruction media and digital tools. Learning space and expected mode deeply impacts the quality of student academic achievements (Mahat & Dollinger, 2018). Effective learning and teaching thrives in a learning space that is flexible and innovative to motivate learners, supports interdisciplinary and collaborative learning, and provides a personalised and inclusive learning environment. As regards instruction media and digital tools, Abdulrahaman et al. (2020) stated that their appropriate use in teaching transformed the environment from a teacher-centred learning to a learner-centred one. Multimedia tools are distributed through various technologies and components, broadly classified as web-based and standalone. Standalone tools are especially useful for teaching and practising new concepts, such as three-dimensional technology for modelling and printing and augmented reality (AR) software. Abdulrahaman et al. (2020) added that the identified barriers to multimedia tools for effective learning and teaching included teachers' lack of confidence and resistance to change, inadequate basic knowledge and ICT skills, limited access to computing resources, and insufficient technical, administrative, and financial support. Moreover, additional challenges exist, such as instructional content, skills, physical environment, and time constraints.

In Table 1, we present differences between

traditional pedagogy and digital pedagogy based on seven key elements of effective teaching and learning as shown in Figure 3. The seven elements represent key concerns for digital transformation of education. The implementation of the proposed digital pedagogy will result in the sustainable digital transformation (SDT) of teaching. The SDT aims at transforming learning to promote self-regulated learning, learner agency, and cognitive load management through the active use of digital technology in inquiry, communication, construction, expression, and promoting computational thinking. Moreover, SDT tends to reshape teaching in or beyond the classroom, such as teacher–student interaction, classroom guidance, learning facilitating, and digital resource utilising, to stir up students' native impulses and digital competency.

This pedagogical transformation is grounded by the evolving role of technology in education, which provides unique opportunities for interactive, personalised, and flexible learning experiences (Schleicher, 2015). The integration of digital tools enhances teaching practices by facilitating more dynamic interactions between teachers and students, optimising learning resources, and enabling continuous assessment and feedback. Moreover, as education systems increasingly rely on digital infrastructure, the adoption of digital pedagogy naturally aligns with the broader goal of building resilient and adaptable learning environments that support lifelong learning. By focusing on developing learners' digital competencies and cognitive skills, this transformation sets foundation for a sustainable shift in teaching practices (Anderson & Dron, 2011).

Digital pedagogy with support of technology transcends the constraints of the traditional pedagogy to facilitate personalised learning and cultivate students self-regulated learning capability. Traditional pedagogy refers to teaching practices that emphasise teacher-centred instructions, where teachers are primary sources of knowledge while students are passive

Table 1 Key concerns of digital pedagogy during digital transformation

Element	Traditional pedagogy	Digital pedagogy
Educational beliefs and focus	Teachers are often positioned as the primary source of knowledge, guiding students through structured content. While there may be opportunities for active participation, students typically rely on teacher's direction (Sawyer, 2014).	Teachers lead the teaching process and emphasise student agency in learning. Students' interest drives education because they make sense out of knowledge and experience in their own way.
Delivery and facilitation approach	A typical presentation–practice–production lesson means delivering content through spoken presentations, explaining concepts, providing information, and offering insights (Harmer, 2007). The teacher is an important source of information on how learners are doing.	Rich content presentation forms including VR and AR learning resources, and personalised teaching contents. Students choose what they will learn, how they will pace their learning, and how they will assess their learning by playing roles of facilitators in the classroom.
Structuring teaching and assessment	Traditional teaching methods, such as lectures, presentations, questioning, and dictation, have been widely used (Richards & Rodgers, 2014). Assessments are often conducted as summative assessments rather than formative assessments, and they rarely address qualitative issues of the learner's progress.	Utilise digital technologies and digital resources to enhance teaching and learning (Kirkwood & Price, 2014). Multiple assessment forms and methods include digital assessment, online exams, assessment of learning, assessment as learning, and assessment for learning (Earl, 2013).
Learning activities and feedback	Teachers retain full control of the classroom and its activities, such as face-to-face activities and communication. Students always get feedback from examinations or summative assessments (Gikandi et al., 2011).	Personalised plans and feedback include learning plans tailored to individual students, and feedback based on data and evidence. Online and offline integrated activities include group cooperation, independent inquiry, and online activity (Hrastinski, 2019).
Learner strategies and involvement	Students usually passively receive information. Students learn important communicative and collaborative skills through group work. Students learn to direct their learning, ask questions, and complete tasks independently.	This includes but is not limited to problem-based learning, project-based learning, inquiry-based learning, and self-directed, independent, and collaborative learning.
Learning space and expected mode	Fixed time and space remain key features of traditional education, where schools and classrooms serve as main learning environments for students (Facer & Selwyn, 2021). Mostly, students' desks and chairs are placed in fixed positions, occasionally rearranged based on needs to facilitate students' communication (Barrett et al., 2019). As for technology which is regarded as external access equipment, the use of it is difficult, and there needs more interaction.	The smart learning environment and the flexible combination of teaching space can automatically adjust appropriate temperature, light, etc. (Kinshuk et al., 2016). TEL space can be either virtual or blended classrooms. The expected mode of their combination is that technology is fully integrated into learning space and curriculum, much like air—simple to use, and highly interactive (Huang et al., 2020).
Instruction media and digital tools	Instruction media include text, graphics, audio and video, slides (Mayer, 2020), and web-based application, and digital tools include collaborative tool and communication tool	Technology involvement needs a synergy between human teachers and trustworthy AI such as human–machine collaboration, which supports students in communicating, constructing, expressing, and creating (Conole, 2013). Intelligent devices include iPads, robots, and wearable devices (Sung et al., 2016). Moreover, digital teaching materials are prevalent tools in teaching and learning, which can dynamically update contents and record interactive trajectories in time. Other trustworthy digital resources include various digital websites and AIGC resources.

Notes. VR: virtual reality, AR: augmented reality, TEL: technology-enhanced learning, AI: artificial intelligence, AIGC: AI-generated content.

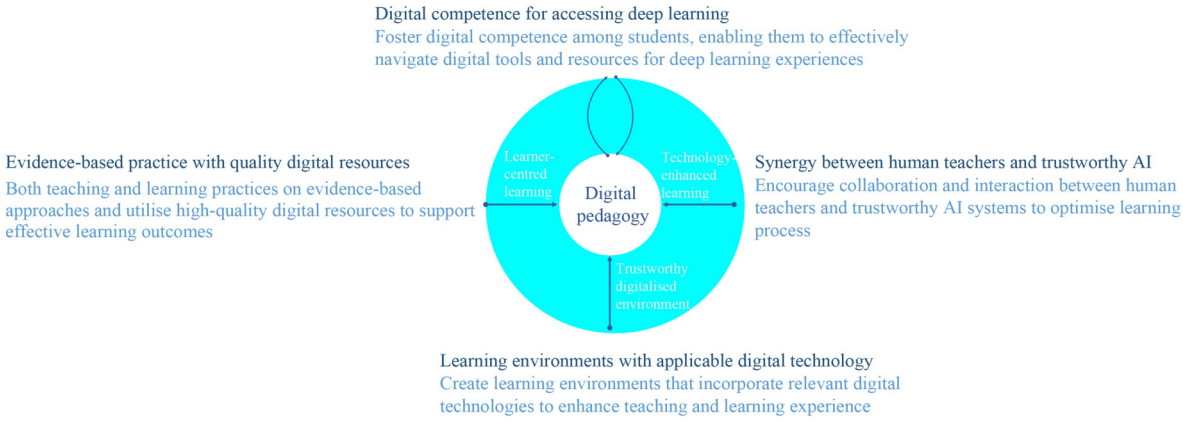

Figure 3 Digital pedagogy framework. AI: artificial intelligence.

recipients of information. Although educational technologies have been utilised in various forms for decades, the distinguished factor of traditional pedagogy lies in limited integration of technology for interactive and learner-driven approaches. The focus remains on direct instruction, summative assessment, and face-to-face communication. By contrast, digital pedagogy emphasises the active role of learners and the use of digital technologies to foster student agency, personalised learning, and collaboration. While technology has become an integral part of education, digital pedagogy specifically refers to approaches where technology is central to reshaping teaching practices, enabling flexible learning environments, and supporting real-time feedback and assessments that go beyond traditional methods (Laurillard, 2012).

6 Digital Pedagogy for Transforming Teaching and Learning

We propose that digital pedagogy is the soul of school transformation. Teachers using classical teaching methods fundamentally focus on student agency and create suitable teaching environments for students. They enhance students' learning engagement and promote improvements in learning effectiveness and efficiency. Teachers especially need to rethink and reimagine new forms of teaching powered by digital technologies in this digital age. The construction of digital pedagogy is triggered by school senior-level management, middle-level leaders, and grassroot-level frontline teachers. Thus, the construction of digital pedagogy follows a distributed form of leadership whereby stakeholders at the top, middle, and bottom levels of school work together to create teaching innovation for development.

Using a handsearching approach of key documents on digital pedagogy and AI in education, we provide an update of the classical pedagogy frameworks mentioned for contemporary educational institutions. Specifically, the review of literature, together with two main published works and sources, guided the formulation of keywords for developing and conceptualising the four components of the DP4SET framework. The first was the prior work of the first author of the current study which discussed and provided a framework—intelligent human–machine synergy in collaborative teaching: utilising the digital twins, avatars or agents, and robots (iSTAR)—for human teachers and machines to effectively collaborate for better outcomes in educational settings (Huang et al., 2023). Huang et al. (2023) proposed four ethical considerations concerning the design of educational technologies such as robots during learning, teaching, and assessment, including: first, responsible human–machine collaboration; second, diversity, inclusion, and fairness; third, trustworthy relationships between AI and human; fourth, AI literacy education. The second focus was related to a report from UNESCO providing guidelines for GenAI in education and research (UNESCO, 2023b). The report proposed a policy framework for integrating GenAI into education comprising eight main elements as follows: first, promoting inclusion, equity, and linguistic and cultural diversity; second, protecting human agency; third, monitoring and validating GenAI systems for education; fourth, developing AI competencies, including GenAI-related skills for learners; fifth, building capacity for teachers and researchers to make proper use of GenAI; sixth, promoting plural opinions and plural expressions of ideas; seventh, testing locally relevant application models and building a cumulative evidence base; eighth, reviewing long-term implications in an intersectoral and interdisciplinary manner.

The two documents mentioned above (Huang et al., 2023; UNESCO, 2023b) provide thorough descriptions and measurable indicators of the four ethical considerations and eight policy elements respectively. The four considerations were established

in terms of policy elements of UNESCO's report after several brainstorming sessions. The wordings were iteratively improved based on the keywords or terminologies used in the document and reviewed literature. After reaching a consensus, the four components were used to develop search terms to describe each of the components. Table 2 presents how the findings from the two documents aided in the development of the four main components of the DP4SET framework.

After developing and conceptualising the four components of the study, search terms were designed by two of the authors to reflect each of the components, including digital competence, deep learning, evidence-based practice, digital resources, learning environments, digital technology, and human–AI synergy. The search terms were used to identify relevant studies that sufficiently described each of the four components. Google Scholar was the main source used in our review, and snowballing sampling method was used. The obtained documents were restricted to the last four years published research (2020–2024). This literature review was not systematic in nature because the focus was on accurately describing the concepts operationalised in the framework as opposed to rigorously presenting the findings.

The proposed digital pedagogy framework, the DP4SET, consists of four essential components emphasising learner-centred learning, TEL, and trustworthy digitalised environments as shown in Figure 3. The four components are digital competence for accessing deep learning, evidence-based practice with quality digital resources, learning environments with applicable digital technology, and synergy between human teachers and trustworthy AI.

Digital competence for accessing deep learning. Digital competence is defined as "the set of knowledge, skills, attitudes, abilities, strategies, and awareness that are required when using ICT and digital media to perform tasks, solve problems, communicate, manage information, collaborate, create and share content, and build knowledge effectively, efficiently, appropriately, critically, creatively, autonomously, flexibly, ethically, and reflectively for work, leisure, participation, learning and socializing" (Ferrari, 2012). Digital competence also involves the safety, ethical, and social dimensions of using digital technologies for learners (Mehrvarz et al., 2021). People with digital competence can use digital media to seek and analyse information, and filter what they receive from cyberspace, and communicate with others using diverse digital tools (Mehrvarz et al., 2021). In the era of AI revolution, educational technologies like GenAI have become increasingly prevalent. Learners are required to equip with digital competence to effectively and safely navigate online space and use AI-related tools (UNESCO, 2024). The meta-analysis by Wu (2023) revealed that the effectiveness of digital technologies on deep learning, such as comprehending and discerning knowledge, was enhanced when an appropriate pedagogy guided instruction. Gaining digital competence enables learners to navigate digital tools and resources for deep learning effectively. The importance of gaining digital competence as integral to future educational sustainability is emphasised in several competency frameworks such as the *Digital Competence Framework for Citizens* (DigComp 2.2) by the European Union (Vuorikari et al., 2022) and the *Digital Literacy Global Framework* (DLGF) by UNESCO (UNESCO, 2018). In contrast to the TPACK framework that emphasises mainly teacher understanding in the use of technology in instruction, digital competence for accessing deep learning provides room for both teachers and learners to develop their digital capacities in engaging with advanced technologies.

Evidence-based practice with quality digital resources. Evidence-based practice is conscientious and judicious use of current best evidence in conjunction with clinical expertise and patient values to guide health care decisions (Cook, 1998). The transfer of the concept of evidence-based practice to the field of education emphasises the systematic development of the

Table 2 Source documents of four components of the DP4SET framework

Document	Digital competence for accessing deep learning	Evidence-based practice with quality digital resources	Learning environments with applicable digital technology	Synergy between human teachers and trustworthy AI
Huang et al., 2023	Adequate AI literacy education		Diversity, inclusion, and fairness	Responsible human–machine collaboration; trustworthy relationships between AI and humans
UNESCO, 2023b	Developing AI competencies for learners including GenAI-related skills; building capacities for teachers and researchers to make proper use of GenAI	Protecting human agency; monitoring and validating GenAI systems for education	Promoting inclusion, equity, and linguistic and cultural diversity; testing locally relevant application models and building a cumulative evidence base	Promoting plural opinions and plural expressions of ideas; reviewing long-term implications in an intersectoral and interdisciplinary manner

Note. GenAI: generative artificial intelligence.

knowledge system that educational research needs to inform practical judgment of teachers. Evidence-based pedagogical practices are beneficial for teachers and students in terms of their academic achievement, interest, and learning trajectories (Wong et al., 2023). In the proposed framework, we advocate for evidence-based teaching practice powered by quality digital resources. This is because integrating digital resources in education is optional even when materials are provided to teachers. It has to be evidence-based. Teachers who need to become more familiar with digital resources may experience difficulty in teaching practice (Drijvers et al., 2013). Hence, our teaching practice with digital resources must be based on evidence. Evidence-based pedagogical practice that allows the utilisation of quality digital resources, such as animations, videos, and reading materials, should be leveraged in the digital environment for curriculum design and assessment (Mishall et al., 2022). For example, a course design that is evidence-based and supported by quality digital resources enhances students' learning experiences in a virtual environment (Johnson et al., 2023). In a digital environment, technology grants teachers access to evidence-based tools and resources, such as modules and tests, which enable them to assess students' performance and modify school curriculum when necessary (Alenezi, 2023). While the TPACK framework calls for professional development in the specific domains of the framework, evidence-based practice with quality digital resources provides a focus for educators who aim at implementing technology to enhance teaching and learning. Professional development programs should prioritise competencies in the use of digital resources and be evidence-based. Moreover, orientation to new technologies should be organised for both teachers and students.

Learning environments with applicable digital technology. To optimise learning, the digital learning environment should be embedded with relevant technologies (Crompton & Sykora, 2021). Technologies appropriate to a specific discipline, subject, and training program should be judiciously employed. Technology should be integrated into learning environment based on its applicability. Teachers should know which technology should be used and how to use such technologies in a digital environment, and they should also be aware of which context to use or not to use a specific technology (Crompton & Sykora, 2021). They need to recognise and harness the potential of digital technology in their daily teaching practices and utilise it effectively (Spiteri & Chang, 2020), which requires teacher trainings on the use of technologies to improve teachers' TPACK (Spiteri & Chang, 2020). We propose a smart learning environment, a new model of instruction, and a modern education system, with applicable intelligent technologies to support pedagogy and cultivate learners adapting to global change and development (UNESCO IITE et al., 2022). The learning environment supported by technology should promote seamless learning without spatial and temporal constraints. An argument against the TPACK framework is the less emphasis on resource imbalance (Cavanagh & Koehler, 2013). Establishing learning environment with applicable digital technology calls on educators to procure appropriate technologies tailored to a specific mode of instruction and learning. That is, the technological infrastructure for teaching and learning purposes should be context specific.

Synergy between human teachers and trustworthy AI. Education should be a fertile ground for human–AI synergy to promote effective learning among students (Holstein & Aleven, 2022). Past evidence has underscored that the partnership between humans and AI tends to be more effective than human and AI alone (Holstein & Aleven, 2022; Kim, 2024). Human and AI are complemented and compensated (Holstein et al., 2023). As an example of teacher–AI synergy, AI, such as conversational agents and AI-based robots, can collaborate with teachers to support students' emotional well-being, including coping with academic stress and anxiety, peer relationships, and self-regulation. AI can also support teachers to make more informed decisions during instructional design by collecting and analysing data from multiple streams. An intelligent human–machine synergy in collaborative teaching combines human and machine intelligence for an enhanced learning outcome (Huang et al., 2023). AI technologies should be used to complement the work of human teachers as a way of team and collaborative teaching (Huang et al., 2023). Notwithstanding, achieving human–AI synergy is far from guaranteed (Holstein et al., 2023). There are instances where the use of AI to complement the work of human teachers yielded negative results (Holstein & Aleven, 2022; Poursabzi-Sangdeh et al., 2021). Hence, we propose a trustworthy AI to achieve educational goals in the interactions between humans and AI (Vincent-Lancrin & Vlies, 2020). Trustworthy AI should bring about a responsible human–machine collaborative relationship from three aspects, including human dignity, data privacy, and technical robustness and safety (Huang et al., 2023). The conditions for AI to empower human demand greater trust and a sustainable synergy between human and machine intelligence (Mercier-Laurent, 2023). Moreover, the shared roles between humans and AI should be apparent for meaningful partnership and instruction. In contrast to the TPACK framework where technology domain has been criticised for being vague, the DP4SET brings to light human–machine collaboration and interaction that is widely advocated in interacting with digital technologies (Huang et al.,

2023). The synergy between human teachers and trustworthy AI is a call for the development of both human intelligence and AI to promote safe and responsible use of appropriate technologies in the classroom for educational purposes.

From Figure 3, we conceptualise digital pedagogy as a technology-enhanced teaching and learning and a learner-centred approach to foster deep learning that is achieved through learning environment with applicable digital technology and evidence-based practice with quality digital resources, digital competence for accessing deep learning, and the synergy between human teachers and trustworthy AI. Digital pedagogy can be enhanced by the advancement of technology with the ultimate goal of improving teaching and learning efficiency. New technologies will emerge in the future and should be used to innovate existing digital pedagogies.

7 Application of the Digital Pedagogy Framework in Chinese Context

Hattie and Clarke (2019) have found that the key factors influencing education encompass socio-cultural aspects, family background, school conditions, and ability levels of both teachers and students. Among these influential factors, society, family, and learning environments factors are difficult to change. However, changing teaching methods and learning styles is more feasible, requiring adjustments from both teachers and students. Additionally, the effective use of information technology in the classroom can improve teaching quality at a relatively low cost.

Huang et al. (2014) conducted an action research on the construction of digital classrooms in the remote and ethnic areas of Qinghai Province in the northwestern China. The study involved 32 teachers from 12 K-12 schools, focusing on Chinese language and digital classroom teaching. The research aimed at implementing the most effective key factors identified in previous studies and maximising their effectiveness in classroom instruction through the full utilisation of digital technology, tools, and resources. The study spanned two years and found that classroom teaching performance, students' learning strategies, and motivation had all improved in the 12 schools involved.

In advocating for future classrooms to embrace an innovative digital pedagogy, Huang et al. (2014) took a fundamental view of visible learning by incorporating the most effective factors for effective teaching into basic components of classroom teaching as shown in Figure 4. With the support of a digital classroom environment, teachers can fully utilise various intelligent tools to better implement teaching process. Students can fully communicate, explore, construct, express, and manage through technology to record and trace their learning data. Teachers can assess learning outcomes by tracing students' learning data and continuously improving their own teaching.

The teaching experiment in Qinghai has formed typical modes of technology-enhanced rural education, including classes delivered remotely, classes guided remotely, classes shared remotely, and independent inquiry classrooms based on cloud classrooms (Huang et al., 2014). Based on a pilot study on visible learning conducted in K-12 rural schools in Qinghai–Xizang Plateau, China, during the COVID-19 pandemic, the significance of reshaping teaching within and beyond the classroom can be observed (Huang et al., 2014). The research shows that the effective use of technology in the classroom can quickly improve quality of education in rural areas at a lower cost.

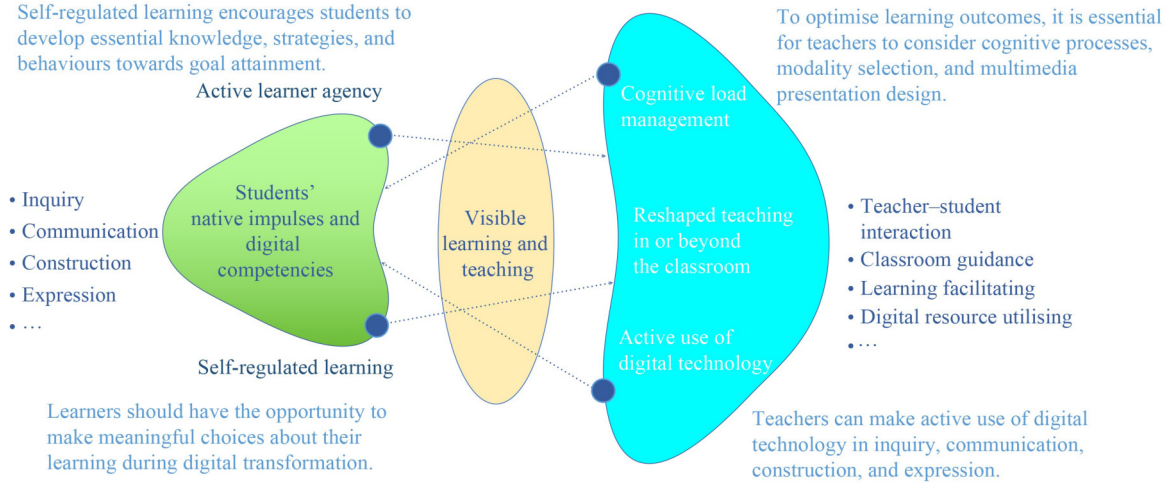

Figure 4 A pilot study of visible learning in K-12 schools of Qinghai–Xizang Plateau, China.

8 Conclusions

The call for the digital transformation of education demands educational revolution using innovative pedagogical strategies. The digital transformation of education requires continuous use of digital, networked, and intelligent technologies and means to transform education system. Nonetheless, there are still persistent problems in infusing teaching and learning practices with technology in many educational settings in the digital age. The application of digital technology is not a means as revealed in the *Global Education Monitoring report* (UNESCO, 2023a). A digital pedagogy to promote digital thinking and deep learning is the soul of educational transformation. The conventional modes of teaching and learning need to be revised in cultivating talents adept with 21st-century competencies such as high-order thinking, collaboration, information literacy, and creativity. In the new teaching revolution with advanced technologies, we should create a learner-centred teaching ecology utilising technologies, diverse teaching methods, and clear instructions. Teaching practice in digital contexts should promote the active use of digital technologies. As a key contribution of the study, we proposed the digital pedagogy framework as the new teaching and learning ecology for modern education systems.

In this study, we illustrated that traditional pedagogy relied on in-person instruction, passive engagement, and paper-based assessments, often leading to superficial learning outcomes. In contrast, digital pedagogy leverages cutting-edge digital technologies, promotes active engagement, facilitates deep learning, and emphasises digital literacy and competence. It also enables self-directed and collaborative learning, utilises digital resources, and offers online and hybrid modes of education. Although past studies have used the terms "e-pedagogy" and "digital pedagogy" interchangeably, we specifically use digital pedagogy throughout the study.

Moreover, we demonstrated in Table 1 about key concerns of digital transformation in education to help educators understand how to smoothly transit to a digital learning environment based on the principles of the digital pedagogy framework. The key concerns are discussed in light of seven highlighted key elements for effective learning and teaching in the digital era. The proposed digital pedagogy aims to promote effective learning and teaching. It is clearly defined who will benefit from and how to use the key tenets in the proposed digital pedagogy framework to improve chances of successful digital transformation of education.

Moreover, the case study presented in the Chinese context signifies the need for educational institutions globally to embrace an innovative digital pedagogy. The proposed digital pedagogy framework provides a foundation for modern education systems to accommodate advanced digital technologies for SDT of education. The future classroom should construct a learning environment with applicable digital technology, foster students' digital competence for accessing deep learning, anchoring teaching, and learning practices on evidence-based approaches supported by quality digital resources, and encourage collaboration and interaction between human teachers and trustworthy AI systems to optimise the learning process.

As mentioned above, a comprehensive approach involving all stakeholders and policymakers should be adopted in implementing digital pedagogy in education systems. School stakeholders and policymakers in education system should adhere to the condition of constructing a digital pedagogy in TEL contexts involving smart learning environments, technology-enhanced learning and teaching, and evidence-based governance. We recommend that future researchers and educators test and contextualise the proposed digital pedagogy framework to build a sustainable learning society.

It is worth noting that the DP4SET framework highlights four key components to consider when integrating digital technology into teaching, and it has been practically tested in real teaching and learning settings. However, this does not imply that the DP4SET framework proposed in this study is absolute or inflexible. On the contrary, the framework is expected to undergo further iteration and refinement through subsequent theory and practice. In future, investigators will delve deeper into the broader implications of digital pedagogy, especially in light of the numerous challenges facing global education and the trend towards digital transformation in education. The related research topics will be further explored and expanded upon.

Acknowledgment This paper was supported by the Major Project of Philosophy and Social Science Research of the Ministry of Education, China (Grant No. 23JZDW12).

Conflict of Interest Ronghuai Huang is a member of the Editorial Board of *Frontiers of Digital Education*, who was excluded from the peer-review process and all editorial decisions related to the acceptance and publication of this article. Peer-review was handled independently by the other editors to minimise bias.

Data Availability Statements The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

Abdulrahaman, M. D., Faruk, N., Oloyede, A. A., Surajudeen-Bakinde, N. T., Olawoyin, L. A., Mejabi, O. V., Imam-Fulani, Y. O., Fahm, A. O., & Azeez, A. L. (2020). Multimedia tools in the teaching and learning processes: A systematic review. *Heliyon*, *6*(11), e05312.

Adarkwah, M. A. (2021). "I'm not against online teaching, but what about us?": ICT in Ghana post COVID-19. *Education and Information Technologies*, *26*(2), 1665–1685.

Alenezi, M. (2023). Digital learning and digital institution in higher education. *Education Sciences*, *13*(1), 88.

Alton-Lee, A. (2003, June). *Quality teaching for diverse students in schooling: Best evidence synthesis (BES)*. Medium Term Strategy Policy Division, Ministry of Education of New Zealand.

Anderson, T., & Dron, J. (2011). Three generations of distance education pedagogy. *International Review of Research in Open and Distance Learning*, *12*(3), 80–97.

Barrett, L. F., Adolphs, R., Marsella, S., & Martinez, A. M. (2019). Emotional expressions reconsidered: Challenges to inferring emotion from human facial movements. *Psychol Sci Public Interest*, *20*(1), 1–68.

Cavanagh, R. F., & Koehler, M. J. (2013). A turn toward specifying validity criteria in the measurement of technological pedagogical content knowledge (TPACK). *Journal of Research on Technology in Education*, *46*(2), 129–148.

Chow, R. S., Lam, C. M., & King, I. (2020). Crisis resilience pedagogy (CRP) for teaching and learning. In: *Proceedings of 2020 IEEE International Conference on Teaching, Assessment, and Learning for Engineering*. Takamatsu: IEEE, 384–391.

Conole, G. (2013). *Designing for learning in an open world*. New York: Springer.

Cook, D. (1998). Evidence-based critical care medicine: A potential tool for change. *New Horiz*, *6*(1), 20–25.

Crompton, H., & Sykora, C. (2021). Developing instructional technology standards for educators: A design-based research study. *Computers and Education Open*, *2*, 100044.

Daniels, H. (2001). *Vygotsky and pedagogy*. London: Routledge.

Dede, C. (2014, December 2). The role of digital technologies in deeper learning. In: *Students at the Center: Deeper learning research series*. Jobs for the Future.

Dewey, J. (1938). *Experience and education*. New York: The Macmillan Company.

Drijvers, P., Tacoma, S., Besamusca, A., Doorman, M., & Boon, P. (2013). Digital resources inviting changes in mid-adopting teachers' practices and orchestrations. *ZDM*, *45*(7), 987–1001.

Earl, L. M. (2013). *Assessment as learning: Using classroom assessment to maximize student learning*. 2nd ed. Dallas: Corwin Press.

Facer, K., & Selwyn, N. (2021). *Digital technology and the futures of education: Towards 'non-stupid' optimism*. Paris: UNESCO.

Ferrari, A. (2012, September 16). *Digital competence in practice: An analysis of frameworks*. Joint Research Centre of the European Commission, 91.

Gikandi, J., Morrow, D., & Davis, N. (2011). Online formative assessment in higher education: A review of the literature. *Computers and Education*, *57*(4), 2333–2351.

Gurney, P. (2007). Five factors for effective teaching. *New Zealand Journal of Teachers' Work*, *4*(2), 88–98.

Hacker, P., Engel, A., & Mauer, M. (2023). Regulating ChatGPT and other large generative AI models. In: *Proceedings of the 2023 ACM Conference on Fairness, Accountability, and Transparency*. Chicago: ACM, 1112–1123.

Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers*, *3*, 275–285.

Harmer, J. (2007). *The practice of English language teaching with DVD*. 4th ed. New York: Pearson Longman ELT.

Hashim, M. A. M., Tlemsani, I., & Matthews, R. (2022). Higher education strategy in digital transformation. *Education and Information Technologies*, *27*(3), 3171–3195.

Hattie, J., & Clarke, S. (2019). Visible learning: Feedback. *The Educational and Developmental Psychologist*, *37*(1), 91.

Holstein, K., & Aleven, V. (2022). Designing for human–AI complementarity in K-12 education. *AI Magazine*, *43*(2), 239–248.

Holstein, K., De-Arteaga, M., Tumati, L., & Cheng, Y. (2023). Toward supporting perceptual complementarity in human–AI collaboration via reflection on unobservables. *Proceedings of the ACM on Human–Computer Interaction*, *7*(CSCW1), 152.

Hrastinski, S. (2019). What do we mean by blended learning? *TechTrends*, *63*, 564–569.

Huang, R., Kinshuk, & Chen, N.-S. (2014). *The new development of technology enhanced learning: Concept, research and best practices*. Heidelberg: Springer.

Huang, R., Liu, D., Tlili, A., Gao, Y., & Koper, R. (2020). *Current state of open educational resources in the "Belt and Road" countries*. Singapore: Springer.

Huang, R., Tlili, A., Xu, L., Ying, C., Zheng, L., Metwally, A. H. S., Chang, T. W., Wang, H. H., Mason, J., Stracke, C. M., Sampson, D., & Bonk, C. J. (2023). Educational futures of intelligent synergies between humans, digital twins, avatars, and robots—The iSTAR framework. *Journal of Applied Learning & Teaching*, *6*(2), 1–16.

Johnson, C. C., Walton, J. B., Strickler, L., & Elliott, J. B. (2023). Online teaching in K-12 education in the United States: A systematic review. *Review of Educational Research*, *93*(3), 353–411.

Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günnemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeffer, J., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., Stadler, M., Weller, J., Kuhn, J., & Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, *103*, 102274.

Kim, J. (2024). Leading teachers' perspective on teacher–AI collaboration in education. *Education and Information Technologies*, *29*, 8693–8724.

Kinshuk, Chen, N.-S., Cheng, I.-L., & Chew, S. W. (2016). Evolution is not enough: Revolutionizing current learning environments to smart learning environments. *International Artificial Intelligence in Education Society*, *26*, 561–581.

Kirkwood, A., & Price, L. (2014). Technology-enhanced learning and teaching in higher education: What is 'enhanced' and how do we know? A critical literature review. *Learning, Media and Technology*, *39*(1), 6–36.

Kivunja, C. (2013). Embedding digital pedagogy in pre-service higher education to better prepare teachers for the digital generation. *International Journal of Sustainability in Higher Education*, *2*(4), 131–142.

Ko, J., & Sammons, P. (2013). *Effective teaching: A review of research and evidence*. Hong Kong: The Hong Kong Institute of Education; Bershire: CfBT Education Trust.

Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge? *Contemporary Issues in Technology and Teacher Education*, *9*(1), 60–70.

Krepf, M., & König, J. (2023). Structuring the lesson: An empirical investigation of pre-service teacher decision-making during the planning of a demonstration lesson. *Journal of Education for Teaching*, *49*(5), 911–926.

Laurillard, D. (2012). *Teaching as a design science: Building pedagogical patterns for learning and technology*. New York: Routlege.

Lee, A. Y., & Hancock, J. T. (2023). Developing digital resilience: An educational intervention improves elementary students' response to digital challenges. *Computers and Education Open*, *5*, 100144.

Mahat, M., & Dollinger, M. (2018). *Mind the gap: Co-created learning spaces in higher education*. Rotterdam: Sense Publishers.

Mayer, R. E. (2020). *Multimedia learning*. 3rd ed. Cambridge: Cambridge Univeristy Press.

McCarthy, A. M., Maor, D., McConney, A., & Cavanaugh, C. (2023). Digital transformation in education: Critical components for leaders of system change. *Social Sciences & Humanities Open*, *8*(1), 100479.

Mehrvarz, M., Heidari, E., Farrokhnia, M., & Noroozi, O. (2021). The mediating role of digital informal learning in the relationship between students' digital competence and their academic performance. *Computers & Education*, *167*, 104184.

Mehta, A., Morris, N. P., Swinnerton, B., & Homer, M. (2019). The influence of values on e-learning adoption. *Computers & Education*, *141*, 103617.

Mercier-Laurent, E. (2023). The future of artificial intelligence: Empowering humanity and help protecting planet. *Computer Sciences & Mathematics Forum*, *8*(1), 38.

Mishall, P. L., Meguid, E. M. A., Khalil, M. K., & Lee, L. M. J. (2022). Transition to effective online anatomical sciences teaching and assessments in the pandemic era of COVID-19 should be evidence-based. *Medical Science Educator*, *32*(1), 247–254.

Morris, P., Park, C., & Auld, E. (2022). COVID and the future of education: Global agencies 'building back better.' *Compare: A Journal of Comparative and International Education*, *52*(5), 691–711.

Mourshed, M., & Barber, M. (2007, September 1). *How the world's best-performing school systems come out on top*. Available online at McKinsey and Company website.

Muijs, D., & Reynolds, D. (2000). School effectiveness and teacher effectiveness in mathematics: Some preliminary findings from the evaluation of the mathematics enhancement programme (primary). *School Effectiveness and School Improvement*, *11*(3), 273–303.

Nurhas, I., Aditya, B. R., Jacob, D. W., & Pawlowski, J. M. (2022). Understanding the challenges of rapid digital transformation: The case of COVID-19 pandemic in higher education. *Behaviour & Information Technology*, *41*(13), 2924–2940.

Pamuk, S. (2012). Understanding preservice teachers' technology use through TPACK framework. *Journal of Computer Assisted Learning*, *28*(5), 425–439.

Pareto, L., & Willermark, S. (2019). TPACK *in situ*: A design-based approach supporting professional development in practice. *Journal of Educational Computing Research*, *57*(5), 1186–1226.

Pettersson, F. (2018). On the issues of digital competence in educational contexts—A review of literature. *Education and Information Technologies*, *23*(3), 1005–1021.

Piaget, J. (1970). *Science of education and the psychology of the child*. Phoenxis: Orion Press.

Poursabzi-Sangdeh, F., Goldstein, D. G., Hofman, J. M., Vaughan, J. W. W., & Wallach, H. (2021). Manipulating and measuring model interpretability. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama: ACM, 1–52.

Redecker, C. (2017, November 28). *European framework for the digital competence of educators: DigCompEdu*. Publications Office of the European Union.

Richards, J. C., & Rodgers, T. S. (2014). *Approaches and methods in language teaching*. 2nd ed. Cambridge: Cambridge University Press.

Sallam, M., Salim, N., Barakat, M., & Al-Tammemi, A. B. (2023). ChatGPT applications in medical, dental, pharmacy, and public health education: A descriptive study highlighting the advantages and limitations. *narra j*, *3*(1), 103.

Saubern, R., Henderson, M., Heinrich, E., & Redmond, P. (2020). TPACK—Time to reboot. *Australasian Journal of Educational Technology*, *36*(3), 1–9.

Sawyer, R. K. (2014). *The Cambridge handbook of the learning sciences*. Cambridge: Cambridge Univesity Press.

Schleicher, A. (2015). Schools for 21st-century learners: Strong leaders, confident teachers, innovative approaches. In: *International Summit on the Teaching Profession*. Paris: OECD Publishing.

Shehata, B., Tlili, A., Huang, R., Adarkwah, M. A., Liu, M., & Chang, T. (2023). How are we doing with student-centered learning facilitated by educational technologies. A systematic review of literature reviews. *Education and Information Technologies*, *29*, 7813–7854.

Spiteri, M., & Chang, R. (2020). Literature review on the factors affecting primary teachers' use of digital technology.

Technology, Knowledge and Learning, *25*(1), 115–128.

Stipek, D. J. (1996). Motivation and instruction. In: Schutz, P. A., Muis, K. R., eds. *Handbook of educational psychology*. New York: Routledge, 85–113.

Stokel-Walker, C., & Noorden, R. V. (2023). What ChatGPT and generative AI mean for science. *Nature*, *614*(7947), 214–216.

Sung, Y.-T., Chang, K.-E., & Liu, T.-C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers & Education*, *96*, 252–275.

Susnjak, T. (2022). ChatGPT: The end of online exam integrity? *arXiv Preprint*, arXiv:2212.09292.

Swallow, M. J. C., & Olofson, M. W. (2017). Contextual understandings in the TPACK framework. *Journal of Research on Technology in Education*, *49*(3–4), 228–244.

Timotheou, S., Miliou, O., Dimitriadis, Y., Sobrino, S. V., Giannoutsou, N., Cachia, R., Monés, A. M., & Ioannou, A. (2023). Impacts of digital technologies on education and factors influencing schools' digital capacity and transformation: A literature review. *Education and Information Technologies*, *28*(6), 6695–6726.

Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the devil is my guardian angel: ChatGPT as a case study of using chatbots in education. *Smart Learning Environments*, *10*(1), 15.

Trevisan, L. V., Eustachio, J. H. P. P., Dias, B. G., Filho, W. L., & Pedrozo, E. Á. (2024). Digital transformation towards sustainability in higher education: State-of-the-art and future research insights. *Environment, Development and Sustainability*, *26*(2), 2789–2810.

UNESCO. (2018, June). *A global framework of reference on digital literacy skills for indicator 4.4.2*. Available from UNESCO website.

UNESCO. (2020). *Education in a post-COVID world: Nine ideas for public action*. Available from UNESCO website.

UNESCO. (2023a). *Global education monitoring report. Technology in education: A tool on whose terms?* Available from UNESCO website.

UNESCO. (2023b). *Guidance for generative AI in education and research*. Available from UNESCO website.

UNESCO. (2023c, July). *Generative AI and the future of education*. Available from UNESCO website.

UNESCO. (2024, September 17). *What you need to know about digital learning and transformation of education*. Available from UNESCO website.

UNESCO IIEP. (2023). *The role of digital technologies in 21st century learning*. Available from UNESCO website.

UNESCO IITE, BNU, & ISTE. (2022). *Report on national smart education framework*. Available from UNESCO website.

United Nations. (2023, Janurary). *Report on the 2022 transforming education summit*. Available from UN website.

Väätäjä, J. O., & Ruokamo, H. (2021). Conceptualizing dimensions and a model for digital pedagogy. *Journal of Pacific Rim Psychology*, *15*, 1–12.

Vincent-Lancrin, S., & Vlies, R. (2020, April 6). *Trustworthy artificial intelligence (AI) in education: Promises and challenges*. OECD Education Working Papers No. 218.

Vuorikari, R., Kluzer, S., & Punie, Y. (2022, March 17). *DigComp 2.2: The digital competence framework for citizens*. Luxemourg: Publications Office of the European Union.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge: Harvard University Press.

Warburton, K. (2003). Deep learning and education for sustainability. *International Journal of Sustainability in Higher Education*, *4*(1), 44–56.

Wong, J. T., Bui, N. N., Fields, D. T., & Hughes, B. S. (2023). A learning experience design approach to online professional development for teaching science through the arts: Evaluation of teacher content knowledge, self-efficacy and STEAM perceptions. *Journal of Science Teacher Education*, *34*(6), 593–623.

Wu, X.-Y. (2023). Exploring the effects of digital technology on deep learning: A meta-analysis. *Education and Information Technologies*, *29*(1), 425–458.

Yu, H. (2023). Reflection on whether Chat GPT should be banned by academia from the perspective of education and teaching. *Frontiers in Psychology*, *14*.

Zancajo, A., Verger, A., & Bolea, P. (2022). Digitalization and beyond: The effects of COVID-19 on post-pandemic educational policy and delivery in Europe. *Policy and Society*, *41*(1), 111–128.

Zuboff, S. (2019). *The age of surveillance capitalism*. London: Profile Books.