ISSN: 2096-3246
Volume 58, Issue 02, 2026

DIGITAL TWIN TECHNOLOGY AND 21ST-CENTURY SKILL DEVELOPMENT IN VOCATIONAL STEM EDUCATION: AN EXPERIENTIAL LEARNING PERSPECTIVE

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Abstract
Digital Twin Technology (DTT) has emerged as a promising educational innovation for bridging theoretical knowledge and practical application within Industry 4.0. Grounded in Kolb's Experiential Learning Theory, this study examined the relationship between students' experiences with DTT and the development of 21st-century skills among 235 second-year students at Shanxi Water Conservancy Vocational and Technical College. Using a quantitative descriptive-correlational design, data were collected through a validated survey measuring the four stages of Kolb's learning cycle and the 4Cs (critical thinking, communication, collaboration, and creativity). Students rated all experiential learning dimensions and 21st-century skills as Very Good, indicating positive perceptions of DTT-supported learning. Spearman's rank-order correlation revealed significant positive relationships between critical thinking and concrete experience, reflective observation, and abstract conceptualization, while collaboration was significantly associated with concrete experience. However, communication and creativity showed no significant correlations with the experiential learning dimensions, suggesting that these competencies require more explicit pedagogical support beyond technology integration alone. The findings demonstrate that DTT effectively supports experiential learning and higher-order thinking but achieves greater educational impact when combined with structured reflective and collaborative learning activities.
Keywords: Digital Twin Technology, Experiential Learning, 21st-Century Skills, STEM Education, Kolb’s Learning Cycle, Vocational Education.

INTRODUCTION
Digital Twin Technology (DTT) has emerged as a promising innovation for enhancing science and technology education by bridging the gap between theoretical knowledge and practical application. A digital twin is a dynamic virtual representation of a physical object, process, or system that continuously exchanges data with its real-world counterpart, enabling real-time monitoring, simulation, prediction, and optimization (Jones et al., 2020; Sharma et al., 2022). Unlike conventional computer simulations, digital twins maintain an evolving connection with physical systems, allowing learners to visualize complex processes, manipulate variables, and evaluate

outcomes within authentic yet risk-free environments. Although DTT has become a cornerstone of Industry 4.0 across manufacturing, healthcare, engineering, and infrastructure, empirical evidence regarding its educational effectiveness—particularly its contribution to experiential learning and the development of 21st-century skills—remains limited. This study therefore investigates the relationship between students' experiences with DTT and their development of critical thinking, communication, collaboration, and creativity through the lens of Kolb's Experiential Learning Theory.

The increasing integration of digital technologies into education has transformed teaching and learning by providing immersive, interactive, and learner-centered environments that extend beyond traditional classroom instruction (Timotheou et al., 2022). Within this context, DTT offers distinct pedagogical advantages because it enables students to engage with realistic virtual representations of scientific and technological systems while receiving immediate feedback on their decisions. Such environments support authentic learning by allowing learners to observe system behavior, test alternative scenarios, and solve complex problems without the financial, safety, or logistical constraints associated with physical laboratories (Jones et al., 2020; Sharma et al., 2022). Consequently, DTT provides opportunities for learners to connect theoretical concepts with practical applications, an essential objective of vocational STEM education.

Kolb's Experiential Learning Theory provides a robust theoretical foundation for understanding how Digital Twin Technology supports learning. According to Kolb (2015), learning is a continuous process consisting of four interconnected stages: Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation. Learners begin by engaging in authentic experiences, reflect on those experiences, develop conceptual understanding, and subsequently apply newly acquired knowledge through experimentation. Digital Twin Technology naturally supports each phase of this learning cycle. Interactive simulations create Concrete Experiences by allowing students to manipulate virtual systems and observe realistic operational outcomes. Real-time visualization and system feedback encourage Reflective Observation, enabling learners to evaluate the consequences of their actions. The interpretation of simulation outputs facilitates Abstract Conceptualization by helping students connect experiential observations with scientific principles and theoretical concepts. Finally, opportunities to modify parameters, test hypotheses, and compare alternative solutions promote Active Experimentation within a safe and controlled virtual environment. Through this iterative process, DTT transforms passive content delivery into meaningful experiential learning that promotes deeper understanding and continuous knowledge construction.

The educational application of DTT also aligns with the growing emphasis on developing 21st-century competencies. Modern science and technology education requires learners not only to acquire disciplinary knowledge but also to demonstrate critical thinking, effective communication, collaboration, and creativity when addressing authentic and complex problems (Binkley et al., 2012). Previous research indicates that immersive digital environments improve conceptual understanding, learner engagement, systems thinking, and practical problem-solving by enabling students to visualize abstract concepts and participate in authentic simulations (Fuller et al., 2020; Jones et al., 2020; Sharma et al., 2022). These characteristics suggest that Digital Twin Technology has considerable potential to foster higher-order cognitive and interpersonal skills while supporting experiential learning. Nevertheless, relatively few empirical studies have examined how students' experiences throughout Kolb's experiential learning cycle contribute to the development of these competencies. Consequently, the pedagogical mechanisms through which DTT facilitates holistic student development remain insufficiently understood.

Addressing this gap, the present study examines the relationship between students' experiences with Digital Twin Technology and their perceived development of 21st-century skills through the framework of Kolb's Experiential Learning Theory. Specifically, the study investigates how students' experiences across the four experiential learning dimensions—Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation—relate to the development of critical thinking, communication, collaboration, and creativity in science and technology courses. In addition, demographic characteristics, including gender, age, academic program, and technology proficiency, are considered to provide a more comprehensive understanding of how DTT supports learning among diverse student populations. By establishing these relationships, this study contributes empirical evidence regarding the pedagogical value of Digital Twin Technology in vocational STEM education and provides practical insights for educators seeking to design technology-enhanced learning environments that effectively integrate experiential learning with the development of essential 21st-century competencies.

METHODOLOGY

This study employed a quantitative descriptive-correlational research design to examine the relationship between students' experiences with Digital Twin Technology (DTT) and the development of 21st-century skills in science and technology courses. A descriptive approach was appropriate for documenting students' perceptions of DTT across the four stages of Kolb's Experiential Learning Cycle, while the correlational component enabled the examination of the strength and direction of the relationships between experiential learning and students' perceived skill development. Because the study sought to determine associations rather than establish causal relationships, a descriptive-correlational design was considered the most appropriate methodological approach.

The study was conducted among second-year students enrolled at Shanxi Water Conservancy Vocational and Technical College, China. The target population consisted of 600 students, from which a sample of 235 participants was selected using purposive sampling. This non-probability sampling technique was chosen because only students who had direct experience using Digital Twin Technology in their science and technology courses could provide meaningful responses to the study objectives. Including participants without exposure to DTT would have limited the validity of the findings regarding experiential learning and skill development. While purposive sampling restricts the generalizability of the results to the broader student population, it enhances the relevance and accuracy of the data by ensuring that all respondents possessed the specific learning experiences under investigation. The sample size was determined using a 95% confidence level and a 5% margin of error, providing sufficient statistical power for the correlational analyses.

Data were collected using a structured, researcher-administered questionnaire composed of three sections. The first section gathered demographic information, including gender, age, academic program, and self-reported technology proficiency. The second section measured students' experiences with Digital Twin Technology based on the four dimensions of Kolb's Experiential Learning Cycle: Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation. The third section assessed students' perceived development of the four core 21st-century competencies—Critical Thinking, Communication, Collaboration, and Creativity.

All questionnaire items were measured using a four-point Likert scale. A four-point response format was intentionally selected to eliminate the neutral midpoint and encourage respondents to express either a positive or negative evaluation of each statement. This forced-choice approach minimizes central tendency bias and provides clearer distinctions in respondents' perceptions, making it particularly appropriate for studies examining attitudes toward educational innovations.

The questionnaire was developed based on the literature on Digital Twin Technology, Kolb's Experiential Learning Theory, and the Partnership for 21st Century Skills framework. To ensure linguistic and cultural appropriateness, both the survey instrument and informed consent forms were translated into Chinese. Content validity was established through evaluation by a panel of three experts in educational technology and research methodology, who reviewed the instrument for clarity, relevance, content coverage, and alignment with the study objectives. Their recommendations were incorporated before pilot testing. A pilot study was subsequently conducted to assess the instrument's reliability, yielding Cronbach's alpha coefficients of 0.80 or higher across all constructs, indicating good internal consistency and reliability for the main study.

Following institutional approval, data were collected through an online survey distributed via email and the institution's Learning Management System (LMS). Participants received an information sheet describing the study's objectives, procedures, voluntary nature of participation, and measures to protect confidentiality. Electronic informed consent was obtained before participants completed the questionnaire.

The collected data were analyzed using Jamovi statistical software. Descriptive statistics, including frequency, percentage, mean, and standard deviation, were used to summarize respondents' demographic characteristics and perceptions of Digital Twin Technology and 21st-century skill development. Spearman's rank-order correlation (r_s) was employed to determine the relationships between students' assessments of DTT and their perceived skill development. Spearman's rho was selected because the variables were measured using ordinal Likert-scale data and the analysis focused on identifying monotonic relationships rather than assuming normally distributed interval-level data. Consequently, Spearman's correlation provided a more appropriate and robust measure of association than parametric alternatives such as Pearson's correlation. All statistical analyses were conducted using a significance level of 0.05.

Ethical considerations were observed throughout the study. Participation was entirely voluntary, and respondents could withdraw from the study at any time without penalty. To ensure confidentiality, all responses were anonymized using alphanumeric codes, and the data were stored in an encrypted database accessible only to the research team for the required five-year retention period. The research protocol received ethical approval from the Institutional Ethics Review Committee (IERC) of Trinity University of Asia under Protocol No. 2025-2nd-CASE_Yi-V1, dated March 31, 2025.

RESULTS AND DISCUSSION

Students' Perceptions of Digital Twin Technology Across Kolb's Experiential Learning Cycle

Table 1 Overall Assessment of Digital Twin Technology by Students in Science and Technology Courses

Dimension	Mean	SD	Verbal Interpretation
Concrete Experience	3.46	0.27	Very Good
Reflective Observation	3.49	0.24	Very Good
Abstract Conceptualization	3.48	0.24	Very Good
Active Experimentation	3.50	0.28	Very Good

Table 1 presents students' perceptions of Digital Twin Technology (DTT) across the four dimensions of Kolb's Experiential Learning Cycle. Overall, the findings indicate highly positive evaluations, with all dimensions receiving a "Very Good" verbal interpretation. Among the four learning dimensions, Active Experimentation obtained the highest mean score (M = 3.50, SD = 0.28),

ISSN: 2096-3246
Volume 58, Issue 02, 2026

followed by Reflective Observation (M = 3.49, SD = 0.24), Abstract Conceptualization (M = 3.48, SD = 0.24), and Concrete Experience (M = 3.46, SD = 0.27). The relatively small variation in the mean scores suggests that students perceived DTT as supporting all phases of experiential learning in a balanced manner rather than emphasizing only a single aspect of the learning process.

The consistently high ratings indicate that students viewed DTT as more than a visualization or simulation tool. Instead, they perceived it as an instructional environment that facilitates continuous learning through authentic experience, critical reflection, conceptual understanding, and practical application. This finding aligns with Kolb's experiential learning theory, which conceptualizes learning as a cyclical process whereby knowledge is constructed through the transformation of experience into meaningful understanding (Kee et al., 2023; Kee & Zhang, 2022).

The favorable rating for Concrete Experience suggests that DTT successfully provides learners with authentic and immersive interactions with scientific systems. By enabling students to manipulate virtual representations of real-world phenomena, digital twins create experiential opportunities that may be impractical, costly, or unsafe to perform in conventional laboratory settings. Such environments enhance learners' engagement with authentic scientific processes while reducing logistical constraints commonly associated with physical experimentation. This finding supports previous studies demonstrating that digital twin technologies effectively replicate real-world environments, thereby promoting experiential engagement and contextualized learning (Pathak & Upadhyay, 2024; Georgiou et al., 2021; Hazrat et al., 2023).

Similarly, the high evaluation of Reflective Observation indicates that students perceived DTT as facilitating critical reflection on their learning experiences. The real-time feedback and dynamic visualization provided by digital twin environments allow learners to compare expected and observed outcomes, identify discrepancies, and refine their understanding through iterative analysis. Such opportunities encourage metacognitive regulation by enabling students to evaluate their decisions before progressing to subsequent learning tasks. This finding is consistent with previous research showing that immersive learning environments enhance reflection, problem-solving, and higher-order thinking when learners receive immediate feedback on their performance (Huang et al., 2024; Cheng et al., 2025). Within Kolb's framework, reflection serves as the critical mechanism through which experience becomes meaningful learning, emphasizing that experiential activities alone are insufficient without opportunities for systematic evaluation.

Students also reported highly positive perceptions of Abstract Conceptualization, suggesting that DTT supports the development of theoretical understanding beyond simple interaction with virtual models. Rather than merely observing simulations, learners appeared capable of synthesizing their experiences into broader scientific concepts and principles. This finding demonstrates that DTT can facilitate the integration of experiential activities with conceptual reasoning, thereby strengthening knowledge construction. Previous studies similarly report that simulation-based and immersive learning environments enhance conceptual understanding when experiential activities are intentionally aligned with instructional objectives and reflective learning strategies (Wörner et al., 2022; Manligoy et al., 2025; Enăchescu et al., 2026). Although earlier research suggests that abstract conceptualization is often the most challenging phase to achieve within immersive environments (Kee et al., 2023), the present findings indicate that students perceived DTT as effectively supporting this cognitive transition.

Among all dimensions, Active Experimentation received the highest mean score, indicating that students regarded DTT as particularly effective in enabling the practical application of newly acquired knowledge. Digital twin environments provide learners with opportunities to manipulate variables, evaluate multiple scenarios, and immediately observe the consequences of their decisions without the risks associated with real-world experimentation. Such capabilities encourage inquiry-based learning, iterative problem-solving, and autonomous exploration, which are central characteristics of learner-centered instruction and Education 4.0. The prominence of Active Experimentation is consistent with previous investigations demonstrating that digital twins are particularly effective in promoting experimentation, decision-making, and practical skill development because they provide safe and flexible environments for repeated testing and refinement of ideas (Cho & Park, 2023; Pathak & Upadhyay, 2024; Ning et al., 2024; Speicher et al., 2026). Similar findings have also been reported in virtual reality-based education, where immersive simulations significantly increased learners' active participation and confidence in applying knowledge to authentic situations (Kiegaldie & Shaw, 2023).

Collectively, the results demonstrate that DTT effectively supports all four stages of Kolb's Experiential Learning Cycle. Rather than functioning as isolated instructional components, concrete experience, reflective observation, abstract conceptualization, and active experimentation appear to operate as interconnected processes that facilitate continuous knowledge construction. This pattern suggests that DTT provides a comprehensive experiential learning environment capable of bridging theoretical instruction with authentic application.

The present findings are consistent with recent literature positioning digital twins as transformative educational technologies capable of integrating immersive simulation with evidence-based pedagogical frameworks (Fromm et al., 2021; Omrany et al., 2025). Previous studies have demonstrated that digital twin environments enhance student engagement, conceptual understanding, self-confidence, and practical competence by allowing learners to experience realistic scenarios while continuously reflecting upon and refining their knowledge (Ning et al., 2024; Speicher et al., 2026). Likewise, qualitative investigations in virtual reality-supported education have shown that immersive learning environments naturally facilitate progression through all four stages of Kolb's experiential learning cycle, thereby strengthening both cognitive and practical learning outcomes (Aguilar & Tafesse, 2026; Sinha, 2023).

Overall, the findings provide empirical support for the educational value of Digital Twin Technology in science and technology education. The uniformly high ratings across all experiential learning dimensions suggest that students perceive DTT as an effective learning environment that simultaneously promotes authentic experience, reflective thinking, conceptual development, and practical experimentation. The particularly strong evaluation of Active Experimentation further highlights the capacity of digital twin environments to transform theoretical knowledge into meaningful practice, reinforcing their potential as innovative instructional tools for developing higher-order thinking and problem-solving competencies in Education 4.0.

Relationship Between Digital Twin Technology and 21st-Century Skill Development

Table 3. Correlation of between students' engagement with Digital Twin Technology (DTT) across Kolb's experiential learning dimensions and their perceived 21st-century skills

		Concrete Experience	**Reflective Observation**	**Abstract Conceptualization**	**Active Experimentation**
Critical Thinking	*ρ*	0.13	0.16	0.17	-0.01
	p-value	0.048	0.015	0.008	0.889
Communication	*ρ*	0.03	0.05	0.11	0.02

	p-value	0.683	0.413	0.097	0.752
Collaboration	*ρ*	0.13	0.02	0.07	0.11
	p-value	0.043	0.773	0.266	0.086
Creativity	*ρ*	0.17	0.04	0.16	0.10
	p-value	0.013	0.540	0.016	0.132

The relationship between students' engagement with Digital Twin Technology (DTT) across Kolb's experiential learning dimensions and their perceived 21st-century skills was examined using Spearman's rank-order correlation. The analysis revealed several statistically significant, albeit weak, positive associations, suggesting that engagement with specific experiential learning processes is related to the development of selected higher-order competencies.

Among the four skills examined, critical thinking demonstrated significant positive correlations with Concrete Experience ($\rho = 0.13$, $p = 0.048$), Reflective Observation ($\rho = 0.16$, $p = 0.015$), and Abstract Conceptualization ($\rho = 0.17$, $p = 0.008$). Although the correlation coefficients indicate modest effect sizes, the consistent pattern across three dimensions suggests that students who engaged more deeply with authentic experiences, reflective analysis, and conceptual reasoning within the digital twin environment also reported stronger critical thinking skills. Notably, the strongest relationship emerged with Abstract Conceptualization, highlighting the importance of transforming experiential activities into theoretical understanding rather than relying solely on experiential engagement. This finding reinforces Kolb's experiential learning theory, which posits that learning is optimized when concrete experiences are complemented by reflection and conceptual interpretation.

The observed relationships are consistent with previous research demonstrating that critical thinking develops most effectively when experiential technologies are integrated with structured reflection and conceptual processing. Cheng et al. (2025), for example, reported that Kolb-based instructional interventions significantly enhanced learners' analytical reasoning, with the greatest gains occurring during the reflective observation and abstract conceptualization phases. Similarly, Huang et al. (2024) found that immersive virtual reality environments promoted higher-order thinking only when learners were provided with opportunities to evaluate their experiences through guided reflection and feedback. These findings collectively suggest that technological immersion alone is insufficient for cultivating critical thinking; rather, meaningful cognitive development depends on instructional designs that encourage learners to interpret, question, and synthesize their experiences. Comparable conclusions have also been reported in inquiry-based and guided-discovery learning environments, where structured scaffolding consistently produced stronger improvements in higher-order thinking than unguided experiential activities (Antonio & Prudente, 2023; Alanazi et al., 2024).

A similar pattern emerged for creativity, which was significantly associated with Concrete Experience ($\rho = 0.17$, $p = 0.013$) and Abstract Conceptualization ($\rho = 0.16$, $p = 0.016$). These findings suggest that students' opportunities to interact with realistic virtual systems and subsequently transform those experiences into conceptual understanding contribute to their ability to generate innovative ideas and alternative solutions. Digital twin environments provide learners with opportunities to visualize complex systems, manipulate variables, and explore multiple scenarios, thereby fostering divergent thinking and creative problem-solving. Nevertheless, the relatively modest magnitude of these relationships indicates that creativity is likely influenced by multiple

instructional and contextual factors beyond technological engagement alone.
The present findings align with Kolb's assertion that creativity emerges from the interaction between experiential encounters and conceptual reasoning rather than from isolated experimentation. Supporting this interpretation, Weerakoon et al. (2025) demonstrated that abstract conceptualization enhances strategic thinking and resourcefulness, whereas concrete experience provides the authentic contexts necessary for innovation. Likewise, studies of project-based and technology-enhanced learning have shown that creativity is strengthened when learners engage in authentic problem-solving supported by reflection, iterative thinking, and conceptual integration rather than by technology-mediated activities alone (Dewra, 2025). Collectively, these findings suggest that DTT contributes to creativity by serving as a catalyst for experiential inquiry, provided that learners are guided toward meaningful interpretation of their experiences.
Collaboration exhibited a statistically significant positive relationship only with Concrete Experience ($\rho = 0.13$, $p = 0.043$). Although weak, this association suggests that shared engagement with virtual representations of real-world systems may encourage collaborative learning through common experiential contexts. Authentic simulations often require learners to discuss observations, compare interpretations, and jointly explore solutions, thereby creating opportunities for collaborative knowledge construction. However, the absence of significant correlations with the remaining experiential dimensions implies that collaboration may depend less on technological immersion itself and more on the instructional strategies through which digital twin activities are implemented.
Conversely, communication did not demonstrate statistically significant relationships with any of the experiential learning dimensions. This finding indicates that while DTT effectively supports individual cognitive engagement, its current implementation may not sufficiently facilitate interpersonal communication or collaborative discourse. Communication is generally developed through structured opportunities for discussion, argumentation, peer feedback, and collaborative decision-making rather than through interaction with digital technologies alone. Consequently, the absence of significant relationships should not be interpreted as a limitation of DTT itself but rather as evidence that communication competencies require explicit pedagogical integration within technology-enhanced learning environments.
This interpretation is consistent with existing literature emphasizing that communication skills develop primarily through intentionally designed social learning experiences. Vale and Barbosa (2023) argue that effective communication emerges when learners actively exchange ideas, justify reasoning, and engage in collaborative dialogue during problem-solving activities. Similarly, project-based learning research has consistently demonstrated that communication improves when students participate in authentic collaborative tasks involving investigation, implementation, reflection, and peer interaction (Dewra, 2025). Although digital twin technologies provide platforms capable of supporting interaction with peers, instructors, and external experts, these technological affordances must be deliberately integrated into collaborative learning designs if communication is to become a measurable educational outcome (Pathak & Upadhyay, 2024; Ješková et al., 2022).
An interesting finding concerns Active Experimentation, which, despite receiving the highest descriptive evaluation in the preceding analysis, did not demonstrate statistically significant relationships with either critical thinking or creativity. This apparent discrepancy suggests that students perceived experimentation within the digital twin environment as engaging and beneficial, yet such engagement alone was insufficient to produce measurable improvements in higher-order cognitive skills. While digital twins provide rich opportunities for manipulating variables, testing scenarios, and exploring system behavior, these activities may not automatically promote deep learning unless accompanied by structured reflection and conceptual processing. Thus, the

educational value of experimentation appears to depend on how effectively experiential activities are connected to opportunities for reasoning, evaluation, and knowledge synthesis.

This finding is supported by previous research indicating that immersive technologies frequently excel in promoting engagement and hands-on interaction but are less effective in developing higher-order cognition when reflective processes are insufficiently incorporated. Reviews of immersive learning environments have noted that many technology-enhanced instructional designs disproportionately emphasize concrete experience and experimentation while providing comparatively limited support for reflective observation and abstract conceptualization (Kee & Zhang, 2022). Similarly, Kee et al. (2023) reported that immersive learning environments produce uneven activation across Kolb's experiential learning stages, with stronger effects typically observed for engagement than for conceptual reasoning. Evidence from simulation-based education likewise suggests that authentic participation alone does not guarantee meaningful learning outcomes; rather, stronger cognitive gains occur when experiential activities are embedded within instructional cycles that explicitly integrate doing, reflection, discussion, and conceptual analysis (Kiegaldie & Shaw, 2023; Davitadze et al., 2021).

Overall, the correlation analysis demonstrates that DTT contributes most strongly to the development of higher-order cognitive skills when experiential engagement is accompanied by reflection and conceptual understanding. Although the observed relationships are relatively weak, their consistency across multiple experiential dimensions supports the theoretical proposition that experiential learning extends beyond technological interaction to include the cognitive processes through which learners interpret and transform experience into knowledge. The findings further suggest that collaboration and, particularly, communication require deliberate pedagogical strategies beyond the technological capabilities of digital twin environments. Consequently, educators seeking to maximize the educational potential of DTT should complement immersive simulations with structured reflective activities, collaborative inquiry, peer discussion, and evidence-based argumentation. Such instructional enhancements may strengthen the contribution of digital twin technologies to the development of comprehensive 21st-century competencies while enabling learners to progress through the complete experiential learning cycle proposed by Kolb.

Digital Twin Technology Pedagogy Support

The findings of the present study suggest that the educational value of Digital Twin Technology (DTT) is determined not solely by its technological capabilities but by the pedagogical approaches through which it is implemented. Although students reported the highest level of engagement in Active Experimentation, this dimension did not demonstrate significant relationships with critical thinking or creativity. This finding indicates that engagement in hands-on digital activities alone may be insufficient to promote higher-order cognitive development. Instead, the effectiveness of DTT appears to depend on instructional designs that intentionally integrate experiential activities with opportunities for reflection, conceptual reasoning, and collaborative knowledge construction.

This interpretation is consistent with Kolb's Experiential Learning Theory, which conceptualizes learning as a continuous cycle in which concrete experience, reflective observation, abstract conceptualization, and active experimentation function as interdependent rather than isolated processes. Accordingly, DTT-based learning activities should extend beyond virtual experimentation to include structured opportunities for students to interpret their experiences, connect observations to disciplinary concepts, and apply newly constructed knowledge to subsequent problem-solving tasks. Such instructional sequencing enables learners to transform experience into meaningful understanding, thereby maximizing the educational potential of digital twin environments.

ISSN: 2096-3246
Volume 58, Issue 02, 2026

The present findings are supported by emerging evidence that the effectiveness of digital twin technologies depends primarily on pedagogical design rather than technological sophistication alone. Recent studies characterize DTT as an educational ecosystem capable of providing authentic, observable, and interactive learning experiences; however, improvements in learning outcomes occur only when these environments incorporate structured guidance, formative feedback, and meaningful learner interaction (Zhang et al., 2024; Chamorro-Atalaya et al., 2024). Similarly, contemporary reviews have shifted from viewing digital twins merely as simulation tools to recognizing them as learner-centered platforms that facilitate adaptive instruction, personalized learning pathways, and continuous access to authentic learning experiences beyond the traditional classroom (Addanki & Corrin, 2023; Zhang et al., 2024). These perspectives reinforce the argument that technology functions as an enabler of learning rather than a substitute for sound pedagogy.

The weak association between Active Experimentation and higher-order thinking further underscores the importance of integrating experiential activities with reflective and conceptual learning processes. Previous investigations based on Kolb's framework consistently demonstrate that experiential engagement produces the strongest educational outcomes when learners actively reflect on their experiences and translate those experiences into conceptual understanding (Rahmi, 2024; Stacey et al., 2024). In immersive learning environments, reflection has been identified as the critical mechanism linking action to cognitive development, with evidence showing that students achieve deeper understanding when experiential activities are accompanied by guided discussion, metacognitive prompts, and conceptual analysis (Kee et al., 2023). Similar conclusions have been reported in nursing education, where instructional approaches combining case analysis, reflective journals, peer simulation, and concept mapping produced significant improvements in critical thinking, communication, and self-directed learning compared with experiential activities implemented in isolation (Cheng et al., 2025). Collectively, these findings suggest that reflection serves as the pedagogical bridge through which experimentation is transformed into higher-order learning.

Evidence from broader technology-enhanced learning research supports this interpretation. Systematic reviews of immersive STEM education have shown that technologies such as virtual reality and simulation improve conceptual understanding and learner engagement most effectively when embedded within scaffolded inquiry frameworks that encourage reflection and metacognitive regulation (Tijani & Adeduyigbe, 2026). Likewise, virtual simulation studies indicate that students progress more successfully through Kolb's experiential learning cycle when instructional activities deliberately integrate repeated experimentation with opportunities for reflection, conceptual synthesis, and subsequent application (Stacey et al., 2024). These findings reinforce the principle that experiential technologies are pedagogically effective only when instructional design intentionally supports the complete learning cycle rather than isolated experiential engagement.

The present findings also highlight the importance of adopting learner-centered instructional strategies when implementing DTT. Inquiry-based, collaborative, and project-based learning approaches appear particularly well suited to leveraging the affordances of digital twin environments because they encourage students to investigate authentic problems, analyze real-time data, generate evidence-based solutions, and communicate their reasoning through collaborative inquiry. Such instructional approaches align naturally with the capabilities of digital twins, which enable learners to manipulate complex systems, evaluate alternative scenarios, and receive immediate feedback while engaging in iterative problem-solving.

Empirical evidence increasingly supports the integration of DTT within these learner-centered pedagogies. Digital twin-supported project environments have been shown to facilitate real-time monitoring, iterative solution validation, adaptive feedback, and personalized learning pathways that respond to individual learner needs (Zhang et al., 2024; Addanki & Corrin, 2023). Quasi-experimental studies further demonstrate that integrating digital twins with project-based instruction significantly improves students' critical thinking, learning experiences, and academic achievement compared with conventional teaching approaches (Zhang et al., 2024). Similarly, inquiry-based learning frameworks have produced substantial improvements in digital literacy, critical thinking, and reflective learning by engaging students in systematic investigation, conceptual analysis, collaborative discussion, and knowledge dissemination (Yasa et al., 2024). Project-based learning research likewise consistently reports positive effects on creativity, teamwork, communication, learner autonomy, and problem-solving because students are required to investigate authentic challenges through sustained inquiry and collaborative reflection (Dewra, 2025; Sah et al., 2024; Rocha et al., 2025).

Evidence specific to digital twin education further reinforces the importance of integrating technology with sound instructional design. Digital twin-supported learning has been associated with improvements in systems thinking, automation competencies, data-driven decision-making, and professional problem-solving, particularly within engineering and technical education (Ning et al., 2024; Speicher et al., 2026). Nevertheless, recent reviews caution that these educational benefits cannot be attributed to technology alone. Effective implementation requires educators who possess the pedagogical competencies necessary to facilitate inquiry, guide reflection, design authentic learning tasks, and provide timely formative feedback. In addition, institutional support through professional development, interdisciplinary collaboration, and appropriate technological infrastructure remains essential for sustaining meaningful DTT integration within higher education (Hazrat et al., 2023; Chamorro-Atalaya et al., 2024; Addanki & Corrin, 2023; Pathak & Upadhyay, 2024).

Taken together, the findings suggest that Digital Twin Technology should be conceptualized as a pedagogical platform rather than merely an instructional technology. While DTT provides immersive and authentic environments that support experiential learning, its contribution to higher-order learning depends on how effectively educators structure inquiry, reflection, collaboration, and conceptual dialogue throughout the learning process. Consequently, successful implementation of DTT requires instructional designs that deliberately integrate authentic experimentation with reflective practice, collaborative discourse, and iterative knowledge construction. Such an approach not only aligns with Kolb's experiential learning framework but also enhances the capacity of digital twin environments to cultivate the critical thinking, creativity, collaboration, and other competencies required for 21st-century education.

Technology Integration and Institutional Readiness

The findings of the present study underscore that the successful implementation of Digital Twin Technology (DTT) extends beyond technological adoption and requires comprehensive institutional readiness. While DTT offers considerable potential to enrich experiential learning through immersive simulation and real-time interaction, its educational effectiveness ultimately depends on the institutional capacity to support its pedagogical integration. Accordingly, sustainable implementation requires coordinated investment in digital infrastructure, faculty capability, curriculum redesign, and organizational support systems.

A fundamental prerequisite for DTT implementation is the availability of robust technological infrastructure. Effective digital twin environments rely on reliable internet connectivity, interoperable hardware and software systems, secure data management, and responsive technical support to enable real-time simulation, visualization, and learner interaction. Without these foundational resources, the interactive and adaptive capabilities that distinguish digital twins from conventional instructional technologies cannot be fully realized. Previous studies similarly identify infrastructure readiness—including network reliability, cybersecurity, data quality, and platform interoperability—as essential conditions for the successful deployment of digital twin ecosystems in higher education (Hazrat et al., 2023; Pathak & Upadhyay, 2024; Tijani & Adeduyigbe, 2026). Moreover, because digital twins are increasingly promoted as mechanisms for extending laboratory access, supporting hybrid learning, and overcoming constraints associated with physical facilities, institutions must ensure that the underlying technological ecosystem is sufficiently scalable and reliable to support these educational objectives (Chamorro-Atalaya et al., 2024; Ning et al., 2024).

Equally important is faculty readiness, which represents one of the most critical determinants of successful technology integration. The findings presented in this study indicate that the educational benefits of DTT are realized not through technology alone but through pedagogically meaningful learning experiences that integrate experimentation with reflection, conceptual reasoning, and collaborative inquiry. Consequently, educators require competencies that extend beyond operational proficiency with digital twin platforms. They must also possess the pedagogical expertise necessary to design authentic learning activities, facilitate inquiry, scaffold reflective learning, and assess higher-order competencies within technology-enhanced environments. Recent bibliometric and systematic reviews consistently identify faculty competencies and professional development as among the most significant gaps in current digital twin implementation, emphasizing that advances in technology must be accompanied by investments in educators' pedagogical capacity (Chamorro-Atalaya et al., 2024; Hazrat et al., 2023). Similar conclusions have been reported across experiential and technology-enhanced learning research, where teacher preparedness and institutional support substantially influence the effectiveness of innovative instructional approaches in developing critical thinking, collaboration, and other higher-order learning outcomes (Rahmi, 2024; Cheng et al., 2025; Sah et al., 2024).

The findings likewise highlight the importance of curriculum alignment as a prerequisite for sustainable DTT integration. Rather than functioning as an isolated instructional resource, digital twins should be embedded within curricula that intentionally promote experiential, inquiry-based, and project-based learning. Such pedagogical models capitalize on the unique affordances of DTT by engaging learners in authentic problem-solving, data interpretation, collaborative investigation, and iterative reflection. Consequently, curriculum design should ensure constructive alignment among intended learning outcomes, instructional activities, and assessment practices so that students are evaluated not only on disciplinary knowledge but also on the development of higher-order competencies. This perspective is supported by contemporary curriculum research, which argues that educational technologies yield meaningful learning gains only when integrated within pedagogical frameworks that emphasize critical thinking, creativity, collaboration, communication, and self-directed learning rather than serving as supplementary technological enhancements to traditional teaching (Dewra, 2025).

Empirical evidence from digital twin education further reinforces the importance of aligning technology with learner-centered pedagogy. Studies have demonstrated that digital twin-supported project-based instruction significantly improves students' critical thinking, learning experiences, academic achievement, and cognitive engagement compared with conventional instructional approaches (Zhang et al., 2024). Likewise, DTT applications in engineering and smart-city education have been associated with enhanced self-confidence, technical competencies, systems thinking, and data-driven problem-solving by providing learners with authentic opportunities to investigate complex real-world systems in simulated environments (Ning et al., 2024; Speicher et al., 2026).

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These findings collectively suggest that the educational contribution of digital twins lies not merely in technological innovation but in their capacity to create authentic contexts that bridge theoretical learning with professional practice.

Despite these educational benefits, the literature consistently acknowledges that institutional implementation remains constrained by financial, technological, and organizational challenges. High infrastructure costs, unequal access to digital resources, limited institutional capacity, resistance to organizational change, and insufficient faculty preparation continue to impede large-scale adoption of technology-enhanced pedagogies (Villamizar, 2025; Sah et al., 2024; Tijani & Adeduyigbe, 2026). Digital twin-specific research similarly identifies technical complexity, data privacy, cybersecurity, governance, and ethical considerations as significant challenges requiring institutional planning and policy development (Addanki & Corrin, 2023; Hazrat et al., 2023; Pathak & Upadhyay, 2024). These findings indicate that successful DTT implementation requires a systems-level approach that addresses technological, pedagogical, and organizational dimensions simultaneously rather than focusing exclusively on technological acquisition.

Overall, the present study reinforces the view that Digital Twin Technology should be implemented as part of a comprehensive institutional strategy for educational innovation rather than as a standalone technological initiative. Institutions seeking to maximize the educational benefits of DTT should prioritize strategic investments in digital infrastructure, sustained faculty professional development, curriculum transformation, and institutional support mechanisms that foster learner-centered and experiential pedagogies. Such investments are essential for enabling digital twin environments to move beyond technological novelty and become sustainable platforms for developing the higher-order competencies required in contemporary science and technology education.

Interdisciplinary Applications of Digital Twin Technology

The findings of this study suggest that the educational value of Digital Twin Technology (DTT) extends beyond science and technology education, highlighting its potential as a transformative pedagogical platform across multiple academic disciplines. While the present investigation was situated within science and technology courses, the experiential, interactive, and data-driven characteristics of DTT are not discipline-specific. Rather, they provide a flexible learning environment capable of supporting authentic inquiry, systems thinking, and evidence-based decision-making in domains where learners are required to understand, analyze, and manage complex real-world phenomena. Consequently, DTT should be viewed not merely as a technological innovation but as an interdisciplinary educational framework that facilitates the integration of theoretical knowledge with professional practice.

The interdisciplinary applicability of DTT arises from its fundamental capability to establish dynamic virtual representations of physical systems through continuous data exchange, real-time simulation, predictive modelling, and iterative experimentation. These affordances enable learners to investigate complex processes, evaluate alternative scenarios, diagnose system behavior, and test solutions within realistic yet low-risk environments before implementing them in real-world contexts. Such capabilities make DTT particularly valuable for disciplines characterized by complexity, uncertainty, and data-intensive decision-making, where experiential learning is essential for developing both disciplinary expertise and higher-order cognitive competencies (Segovia & García, 2022; Yao et al., 2023; Chande, 2024). Rather than serving solely as visualization technology, digital twins create learning ecosystems in which students actively construct knowledge through continuous interaction with authentic systems.

Current scholarship increasingly demonstrates the interdisciplinary reach of digital twin applications.

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Although engineering and manufacturing remain the most mature areas of implementation, recent studies document expanding applications in healthcare, architecture, environmental management, transportation, smart cities, business analytics, and higher education (Dihan et al., 2024; Iliuţă et al., 2024; Rajamäki, 2024). In engineering education, digital twins have been employed to strengthen students' understanding of product life cycles, predictive maintenance, industrial automation, and systems engineering while simultaneously developing multidisciplinary problem-solving competencies aligned with Industry 4.0 (Hazrat et al., 2023). Similarly, health professions education increasingly conceptualizes digital twin technologies as virtual human ecosystems that integrate medicine, computer science, engineering, behavioral sciences, ethics, and health informatics to support clinical reasoning, personalized healthcare, and evidence-informed decision-making (Rajamäki, 2024). These developments illustrate that DTT naturally transcends disciplinary boundaries by addressing problems that require integrated knowledge from multiple domains.

Comparable trends are evident within the built environment and sustainability disciplines. Digital twin technologies have been applied to architecture, engineering, and construction (AEC) to support lifecycle management, energy optimization, predictive maintenance, and sustainable infrastructure development, all of which require collaboration among architects, engineers, environmental scientists, and information specialists (Mousavi et al., 2024). Likewise, smart campus initiatives demonstrate how digital twins facilitate interdisciplinary collaboration by integrating environmental monitoring, spatial analytics, mobility data, and resource management into unified learning environments where faculty, students, industry partners, and institutional stakeholders jointly investigate complex organizational challenges (Mohammadi et al., 2024). These examples underscore the capacity of DTT to serve as a common platform through which diverse disciplinary perspectives converge to address authentic societal and organizational problems.

The interdisciplinary potential of DTT closely aligns with the principles of Education 4.0, which advocates learner-centered pedagogies that prepare graduates for increasingly complex, technology-driven, and interconnected professional environments. Education 4.0 emphasizes the development of both disciplinary expertise and transferable competencies—including critical thinking, collaboration, creativity, communication, systems thinking, and lifelong learning—through authentic, technology-enhanced educational experiences (González-Pérez & Ramírez-Montoya, 2022). Within this framework, emerging technologies are not regarded as instructional endpoints but as catalysts for creating learning environments that promote innovation, interdisciplinary collaboration, and adaptive problem-solving across diverse professional contexts (Lopez et al., 2021). The characteristics of DTT closely correspond to these educational priorities by enabling students to engage with complex systems, interpret real-time information, and make evidence-informed decisions within authentic experiential settings.

The pedagogical approaches most frequently associated with Education 4.0 further reinforce the interdisciplinary value of digital twin environments. Inquiry-based, project-based, problem-based, and experiential learning approaches consistently demonstrate positive effects on critical thinking, creativity, collaboration, communication, learner autonomy, and complex problem-solving because they position students as active participants in investigating authentic challenges rather than passive recipients of information (Dewra, 2025; Rocha et al., 2025; Alali, 2024). These instructional models naturally complement digital twin environments by allowing learners to investigate multidisciplinary problems, evaluate competing solutions, reflect upon outcomes, and iteratively refine their understanding through collaborative inquiry. Interdisciplinary education research similarly argues that authentic learning environments capable of integrating multiple knowledge domains foster greater adaptability, systems thinking, and deeper conceptual understanding than discipline-specific

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instructional approaches (Shenbagavalli, 2025). Consequently, DTT provides an educational infrastructure through which interdisciplinary pedagogies can be implemented more effectively.
Empirical evidence across educational contexts further supports this interpretation. Technology-enhanced project environments grounded in Education 4.0 principles have been shown to strengthen teamwork, communication, creativity, organizational skills, and learner autonomy while promoting innovation through collaborative problem-solving (Silva et al., 2021). Similarly, STEAM-oriented project-based learning environments have demonstrated significant improvements in engineering students' collaborative competencies, creative thinking, and problem-solving abilities, while technology-supported experiential learning in business and economics education has been associated with enhanced entrepreneurial thinking, digital literacy, and interdisciplinary decision-making (Oanh & Dang, 2025; Fermaisuri et al., 2026). Although these studies employ different technological platforms, they converge on a common conclusion: authentic, technology-supported learning environments are most effective when they facilitate collaboration across disciplinary boundaries while engaging students in solving complex real-world problems.
Taken together, the present findings and the broader body of literature position Digital Twin Technology as a versatile pedagogical platform capable of supporting interdisciplinary learning within the broader vision of Education 4.0. Rather than being confined to science and technology education, DTT offers a flexible framework for integrating experiential learning, systems thinking, and data-informed inquiry across diverse academic and professional fields. As contemporary societal challenges increasingly transcend traditional disciplinary boundaries, educational institutions should leverage digital twin environments to cultivate graduates who can synthesize knowledge across domains, collaborate effectively with diverse stakeholders, and develop innovative solutions to complex global problems. In this regard, the educational significance of DTT lies not only in its technological sophistication but also in its capacity to transform higher education into a more interdisciplinary, authentic, and future-oriented learning ecosystem.

LIMITATIONS AND FUTURE RESEARCH

Despite the promising findings, several limitations should be considered when interpreting the results of this study. First, the study relied on students' self-reported perceptions of Digital Twin Technology (DTT) and their perceived development of 21st-century skills. Although self-assessment provides valuable insights into learners' experiences, it may not fully reflect actual improvements in critical thinking, communication, collaboration, and creativity. Future studies should complement perceptual measures with objective assessments, performance-based evaluations, or authentic learning tasks to provide stronger evidence of the educational effectiveness of DTT.
Second, the study was conducted within a specific educational context involving science and technology courses, which may limit the generalizability of the findings to other disciplines, educational levels, or institutional settings. Differences in curriculum design, learner characteristics, technological readiness, and instructional practices may influence the effectiveness of DTT implementation. Multi-institutional and cross-disciplinary studies are therefore recommended to determine whether the observed relationships are consistent across diverse educational contexts.
The implementation of DTT also presents practical challenges that extend beyond pedagogy. Effective deployment requires reliable digital infrastructure, specialized software, compatible hardware, and stable internet connectivity, resources that may not be equally available across educational institutions. Such disparities may limit equitable access to DTT, particularly in resource-constrained environments. In addition, successful implementation depends on faculty readiness and sustained professional development, as educators require both technical proficiency and pedagogical expertise to integrate digital twins effectively into experiential learning environments.

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Future research should examine the long-term impact of DTT on students' learning outcomes using longitudinal and experimental research designs. Investigations comparing DTT with other immersive technologies, such as virtual reality, augmented reality, and artificial intelligence–supported learning systems, would further clarify its relative educational value. Moreover, future studies should explore pedagogical models that intentionally integrate collaborative learning, project-based learning, and inquiry-based learning within digital twin environments to strengthen communication and collaboration, which demonstrated limited associations in the present study. Finally, expanding DTT applications to disciplines beyond STEM, including the health sciences, business, environmental studies, and the humanities, would provide a broader understanding of its potential to support interdisciplinary experiential learning and the development of workforce competencies aligned with Education 4.0.

CONCLUSIONS

This study provides empirical evidence that Digital Twin Technology (DTT) serves as an effective pedagogical innovation that enhances experiential learning and supports the development of essential 21st-century competencies in science and technology education. Students reported highly positive perceptions across all four dimensions of Kolb's Experiential Learning Cycle—Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation—indicating that DTT functions not merely as a technological simulation tool but as an integrated learning environment that promotes authentic, learner-centered experiences. The significant relationships between DTT and critical thinking further demonstrate that immersive digital environments can stimulate higher-order cognitive processes when experiential learning is intentionally embedded into instructional practice. Although students perceived improvements in communication, collaboration, and creativity, the limited significant relationships observed for some competencies suggest that these skills require deliberate pedagogical strategies, such as collaborative inquiry, project-based learning, and structured reflective activities, to maximize the educational benefits of DTT.

The findings extend the application of Kolb's Experiential Learning Theory within digital learning environments by demonstrating how Digital Twin Technology can operationalize the experiential learning cycle to facilitate meaningful knowledge construction and skill development. Beyond contributing to the growing body of literature on educational applications of digital twins, this study provides practical insights for educators, curriculum developers, and institutional leaders seeking to integrate emerging technologies into science and technology education. Educational institutions may draw from these findings by adopting DTT as part of learner-centered instructional approaches that combine authentic simulations with reflective, collaborative, and inquiry-based learning experiences. However, successful implementation requires adequate technological infrastructure, institutional support, and continuous faculty development to ensure that technological innovation is accompanied by effective pedagogical practice.

Overall, this study highlights the potential of Digital Twin Technology to support educational transformation in the context of Education 4.0 and the evolving demands of Industry 4.0. As higher education increasingly embraces digital innovation, DTT offers a promising platform for bridging theoretical knowledge with authentic practice while preparing students with the competencies required for complex and technology-driven workplaces. The findings also provide a foundation for future research examining the effectiveness of DTT across diverse disciplines, educational contexts, and instructional models, thereby contributing to the continued advancement of experiential learning and digital pedagogy in higher education.

RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to enhance the integration

of Digital Twin Technology (DTT) in higher education and guide future research.
First, educators are encouraged to integrate DTT within learner-centered pedagogical approaches grounded in Kolb's Experiential Learning Cycle. While the findings demonstrate that DTT effectively supports experiential learning and critical thinking, communication and collaboration may require more intentional instructional design. Accordingly, instructors should incorporate inquiry-based, project-based, and collaborative learning activities that require students to discuss, justify, and reflect on their decisions while interacting with digital twin environments.
Second, higher education institutions should invest in the technological infrastructure and professional development necessary for sustainable DTT implementation. Reliable digital infrastructure, appropriate software and hardware, and continuous faculty training are essential to maximize the educational benefits of digital twins. Institutions should also integrate DTT into curriculum planning and instructional design to ensure that technology use is aligned with intended learning outcomes and the development of 21st-century competencies.
Finally, future research should extend the present investigation by employing experimental or longitudinal research designs to establish the long-term effects of DTT on students' cognitive, technical, and professional competencies. Comparative studies involving other emerging technologies, such as virtual reality, augmented reality, and artificial intelligence, may provide further evidence of the relative effectiveness of DTT. Researchers are likewise encouraged to examine the application of DTT across different academic disciplines, educational levels, and institutional contexts to determine its broader educational value and support the development of interdisciplinary teaching and learning models.

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