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Review Article

The role of digital twin technology in nursing practice, education, and research

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ABSTRACT

Background: Digital twin technology, a virtual real-time representation of a physical entity, is gaining traction in healthcare, yet its potential in nursing practice remains underexplored.
Objective: This review examines current and potential applications of digital twins in nursing, including benefits, challenges, and integration pathways.
Method: An integrative review synthesised empirical and theoretical literature from PubMed, CINAHL, Scopus, IEEE Xplore, and Web of Science (2015 to 2025), alongside grey literature, with data extracted and analysed thematically.
Results: Digital twins show potential across patient monitoring, workflow optimisation, education, patient safety, and research, though challenges persist around data interoperability, privacy, consent, and workforce readiness.
Conclusion: Digital twins offer transformative opportunities for nursing, requiring interdisciplinary collaboration, curriculum integration, and robust regulatory frameworks.

Introduction

The nursing profession stands at the forefront of healthcare delivery, providing continuous, comprehensive, and compassionate care to patients across a wide range of diverse settings. As healthcare systems worldwide grapple with increasing complexity driven by aging populations, chronic disease burden, technological advancements, and workforce shortages, nurses face mounting pressures to deliver high-quality care while managing heavy workloads and preventing burnout (Alrehaili et al., 2024). In this context, technological innovation has become not merely advantageous but essential to support and optimize nursing practice (Booth et al., 2021).

Among emerging technologies, digital twin (DT) has garnered considerable attention for its transformative potential in healthcare. Originating in engineering and manufacturing sectors, digital twin refers to a virtual, dynamic replica of a physical entity that is continuously updated with real-time data from sensors, devices, and information systems (Grieves & Vickers, 2016). In healthcare, this concept extends to creating virtual representations of patients, clinical environments, or entire healthcare systems, enabling simulation, prediction, and personalization of care pathways (Venkatesh et al., 2022).

While digital twin applications have been extensively documented in medicine, surgery, and cardiology, particularly for surgical planning, cardiovascular modelling, and precision medicine, its role in nursing remains nascent and underexplored (Bruynseels et al., 2018). This gap is noteworthy given that nursing is inherently relational, process-driven, and data-intensive, making it particularly well-suited to benefit from digital twin's capabilities

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in patient monitoring, predictive analytics, workflow optimization, and simulation-based training (Gu et al., 2023). Moreover, as nursing practice increasingly embraces informatics and digital health tools, understanding how digital twin can enhance nursing-sensitive outcomes becomes critical.

Despite growing interest in healthcare digitalization, several barriers hinder the adoption of digital twin in nursing. These include technical challenges related to data integration and interoperability, ethical concerns surrounding patient privacy and algorithmic accountability, and workforce-related issues such as limited digital literacy and resistance to change (Ronquillo et al., 2021). Furthermore, there is insufficient evidence on how digital twin can be practically implemented in nursing contexts, what benefits it may deliver, and what safeguards are necessary to ensure responsible use.

The current healthcare landscape demands innovative solutions that can simultaneously improve patient outcomes, enhance workforce sustainability, and optimize resource utilization. Digital twin technology offers precisely such potential, yet its application in nursing lacks comprehensive synthesis. This narrative review addresses this gap by examining the state of knowledge on digital twin in nursing, exploring its applications across clinical practice, education, and research domains. The review identifies key opportunities and challenges and proposes evidence-informed pathways for integration. The primary aim is to provide nurses, educators, administrators, and policymakers with a comprehensive understanding of digital twin's potential to transform nursing practice. Specific objectives include: (a) to describe the conceptual foundations of digital twin in healthcare and nursing contexts; (b) to synthesize current and potential applications of digital twin across nursing practice, education, and research; (c) to identify benefits, opportunities, and value propositions of digital twin for nursing; (d) to examine technical, ethical, and workforce-related challenges to implementation; and (e) to propose future directions for research, education, and policy development to facilitate responsible adoption of digital twin in nursing.

Conceptual background of digital twin in healthcare and nursing

Digital twin technology represents a convergence of several advanced computational approaches, including Internet of Things (IoT), artificial intelligence (AI), machine learning, and real-time data analytics (Barricelli et al., 2019). In healthcare, a digital twin integrates continuous streams of patient data, including vital signs, laboratory results, imaging studies, genomic information, and patient-reported outcomes, with sophisticated computational models to create a dynamic, evolving virtual representation (Croatti et al., 2020).

Unlike static electronic health records (EHRs), which primarily serve as repositories of historical information, digital twins are dynamic, adaptive, and predictive (Adetunji & Odili, 2024). They continuously learn from new data inputs, adjust their models accordingly, and can simulate various clinical scenarios to inform decision-making (Liu et al., 2019). For instance, a patient's digital twin might integrate real-time glucose monitoring data with dietary intake, activity levels, medication adherence, and genetic markers to predict glycemic trends and recommend personalized interventions (El Saddik et al., 2021).

In the nursing context, digital twin applications extend beyond individual patient modeling to encompass broader, system-level applications. These include virtual representations of hospital wards for workflow optimization, digital models of nursing teams for workload balancing, and simulated clinical environments for education and training (Nepomuceno et al., 2024). The technology enables nurses to visualize complex, multidimensional patient data in intuitive formats, anticipate clinical deterioration before overt symptoms manifest, and test care interventions virtually before implementing them in practice.

The theoretical underpinning of digital twins in nursing aligns closely with established nursing theories and frameworks. For example, the Technology Acceptance Model suggests that perceived usefulness and ease of use influence the adoption of new technologies by nurses (Davis, 1989; Holden & Karsh, 2010; Labrague & Al Harrasi, 2025; Legris et al., 2003; Yuanyuan et al., 2026). Similarly, the Synergy Model in nursing emphasizes matching patient characteristics and needs with nurse competencies, a process that digital twins can enhance by providing comprehensive, real-time patient profiles (Curley, 2007). Furthermore, digital twins support the principles of evidence-based practice by enabling the rapid simulation and evaluation of clinical interventions before implementation (Armeni et al., 2022).

From a technical perspective, a functional digital twin system in nursing requires several core components: data acquisition infrastructure (including sensors, wearables, and monitoring devices), data integration and storage platforms, computational models and algorithms, visualization interfaces, and feedback mechanisms (Laamarti et al., 2020). The system must operate in real-time or near-real-time, maintain data security and privacy, ensure interoperability with existing health information systems, and provide actionable insights that are clinically meaningful and easily interpretable by nurses (Karakra et al., 2019). In terms of the forms digital twins take in practice, implementations vary considerably. At the most immersive end, digital twin platforms may incorporate virtual reality (VR) head-mounted displays that allow clinicians or nursing students to interact with three-dimensional virtual patient environments. Many clinical digital twin applications operate through two-dimensional audiovisual platforms presented on standard workstations, providing dynamic dashboards of patient data, simulated vital signs waveforms, and alert systems. Interactive online platforms are also used in nursing education for asynchronous digital twin simulations accessible via standard web browsers. From an algorithmic output perspective, digital twin analysis may be presented as: (a) dynamic graphs embedded in patient management systems highlighting deteriorating physiological trajectories; (b) color-coded alert systems integrated into ward monitoring infrastructure; (c) natural language clinical decision support prompts; and (d) continuously updated risk stratification scores. Examples include Siemens Healthineers digital twin applications for hospital workflow simulation and Philips HealthSuite for patient monitoring. Hardware requirements range from high-specification computing clusters for real-time physiological simulation to standard clinical workstations for dashboard-based alerting systems.

Methods

Design

This research is an integrative review conducted in accordance with the established integrative review methodology of Whittemore and Knafl (2005). The integrative review is the broadest type of research review, permitting the simultaneous inclusion of diverse methodological literature including empirical studies (quantitative, qualitative, and mixed methods), theoretical papers, and grey literature, to generate new frameworks, perspectives, and comprehensive understanding of an emerging phenomenon (Whittemore & Knafl, 2005). This design is particularly appropriate for digital twin technology in nursing, where the evidence base spans multiple disciplines and a narrow systematic review would risk excluding foundational conceptual and technical literature essential for understanding the field. The framework comprises five stages: (a) Problem Identification; (b) Literature Search; (c) Data Evaluation; (d) Data Analysis; and (e) Presentation. Each stage is addressed in the subsections of Methods Section below. Unlike systematic reviews, integrative reviews permit the critical synthesis of theoretical and empirical literature together, generating new conceptual frameworks that neither source type alone could produce.

Search strategy

A comprehensive and structured literature search was conducted across multiple electronic databases to identify relevant publications. Databases searched included PubMed/MEDLINE, CINAHL (Cumulative Index to Nursing and Allied Health Literature), Scopus, IEEE Xplore, and Web of Science. The search encompassed literature published between January 2015 and March 2025. The 2015 start date was selected because this period coincides with the initial emergence of digital twin terminology in engineering contexts and its first meaningful applications in healthcare. Prior to 2015, the concept existed under different nomenclature (e.g., virtual physiological models and patient simulation) with limited integration of IoT, real-time data streams, and AI components that define contemporary digital twin systems. The 2015-2025 window therefore captures a decade of conceptual evolution, from foundational definitions to early healthcare implementations, ensuring the review reflects the full developmental arc of digital twin technology in nursing and healthcare contexts.

The search strategy utilized both controlled vocabulary terms and keywords, adapted appropriately for each database. For PubMed/MEDLINE, controlled vocabulary (MeSH) terms included: “nursing informatics", “clinical decision support systems", “patient monitoring", and “simulation training". For CINAHL, CINAHL Subject Headings included “nursing informatics” and “patient monitoring systems". For Scopus, Embase, and Web of Science, subject-specific thesaurus terms were adapted where available. Free-text keywords across all databases included: “digital twin", “virtual patient", “patient simulation", “nursing", “nursing practice", “nursing education", “nursing informatics", “healthcare technology", “predictive analytics", “personalized care", “precision nursing", “clinical decision support", and “patient monitoring". Boolean operators (AND, OR) were employed to combine search terms effectively.

Inclusion and exclusion criteria

Studies and documents were included if they met the following criteria: (a) focused on digital twin technology, virtual patient modelling, or closely related concepts; (b) discussed applications relevant to nursing practice, education, or research; (c) published in English; (d) available as full text; and (e) published between 2015 and 2025. Both empirical studies (quantitative, qualitative, and mixed methods) and conceptual papers were included to provide comprehensive coverage of this emerging field, consistent with integrative review methodology.

Materials were excluded if they: (a) focused exclusively on digital twin applications in nonhealthcare sectors without clear relevance to nursing; (b) were opinion pieces without substantive discussion or analysis; (c) were duplicate publications; or (d) were inaccessible despite reasonable efforts to obtain them.

Selection process and data extraction

Stage 2 of the integrative review framework encompasses the literature search and selection process. Initial screening involved two independent reviewers (D.B.O. and A.C.D.) assessing titles and abstracts against the inclusion and exclusion criteria. Disagreements at the title/abstract screening stage were resolved through discussion; where consensus could not be reached, the record was advanced to full-text review. A full-text review was then conducted for all records passing initial screening. Disagreements at full-text stage were resolved through discussion and, where necessary, adjudication by a third reviewer. Given the emerging nature of the topic and the relatively limited nursing-specific literature, the review adopted an inclusive approach, incorporating articles on digital twins in healthcare more broadly where implications for nursing could be reasonably inferred. Grey literature sources were identified through hand-searching of reference lists of included articles, searching grey literature databases (including OpenGrey and Google Scholar), and reviewing technical reports from relevant professional organizations (e.g., International Council of Nurses and American Nurses Association).

The initial database search yielded 487 records. Following removal of 143 duplicates, 344 records were screened at title and abstract level. Of these, 298 were excluded for not meeting inclusion criteria (not relevant to nursing or healthcare, non-English language, or outside the 2015-2025 date range), leaving 46 records for full-text review. A further 29 records were excluded at full-text stage: 15 focused exclusively on nonhealthcare digital twin applications without nursing relevance; eight were opinion pieces without substantive analysis; and six were inaccessible despite reasonable retrieval efforts. Seventeen peer-reviewed articles met all inclusion criteria and were included in the final synthesis. These were supplemented by 12 grey literature sources identified through hand-searching, giving a total of 29 sources informing the review. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses—Integrative Review (PRISMA-IR) flow diagram illustrating the complete literature identification, screening, eligibility assessment, and inclusion process is presented as Figure 1.

Stage 3 of the framework involves data evaluation. Given the heterogeneity of included sources, spanning empirical studies, theoretical papers, and grey literature, formal quality appraisal using a standardized tool (e.g., CASP) was not applied, consistent with established integrative review practice (Whittemore & Knafl, 2005). Instead, source credibility and rigor were evaluated holistically throughout the synthesis process, considering factors such as publication in peer-reviewed journals, clarity of methodology, relevance to the review question, and recency of evidence. Sources judged as low credibility were excluded; no included source was considered so methodologically weak as to undermine the overall synthesis.

Data extraction, Stage 4a of the framework, was conducted using a structured template applied consistently to each included source. Items extracted from each article comprised: (a) citation details (authors, year, country of origin, and journal/source type); (b) study design or article type (empirical: quantitative, qualitative, or mixed methods; or conceptual/theoretical); (c) whether the article was specific to nursing or applied more broadly to another health profession or general healthcare; (d) digital twin application domain addressed (e.g., patient monitoring, education, workforce, and research); (e) key findings and conclusions directly relevant to nursing practice, education, or research; and (f) reported limitations and contextual factors affecting generalizability.

Data synthesis and analysis

Stage 4 (Data Analysis) of the integrative review framework was implemented through a structured thematic synthesis process. Thematic analysis was employed to synthesize findings across the diverse literature identified, enabling the development of a comprehensive understanding of digital twin technology’s role in nursing.

The thematic synthesis comprised four iterative stages. In Stage 4a (Data Reduction), each included source was read in full by two independent reviewers (D.B.O. and A.C.D.), who assigned ini-

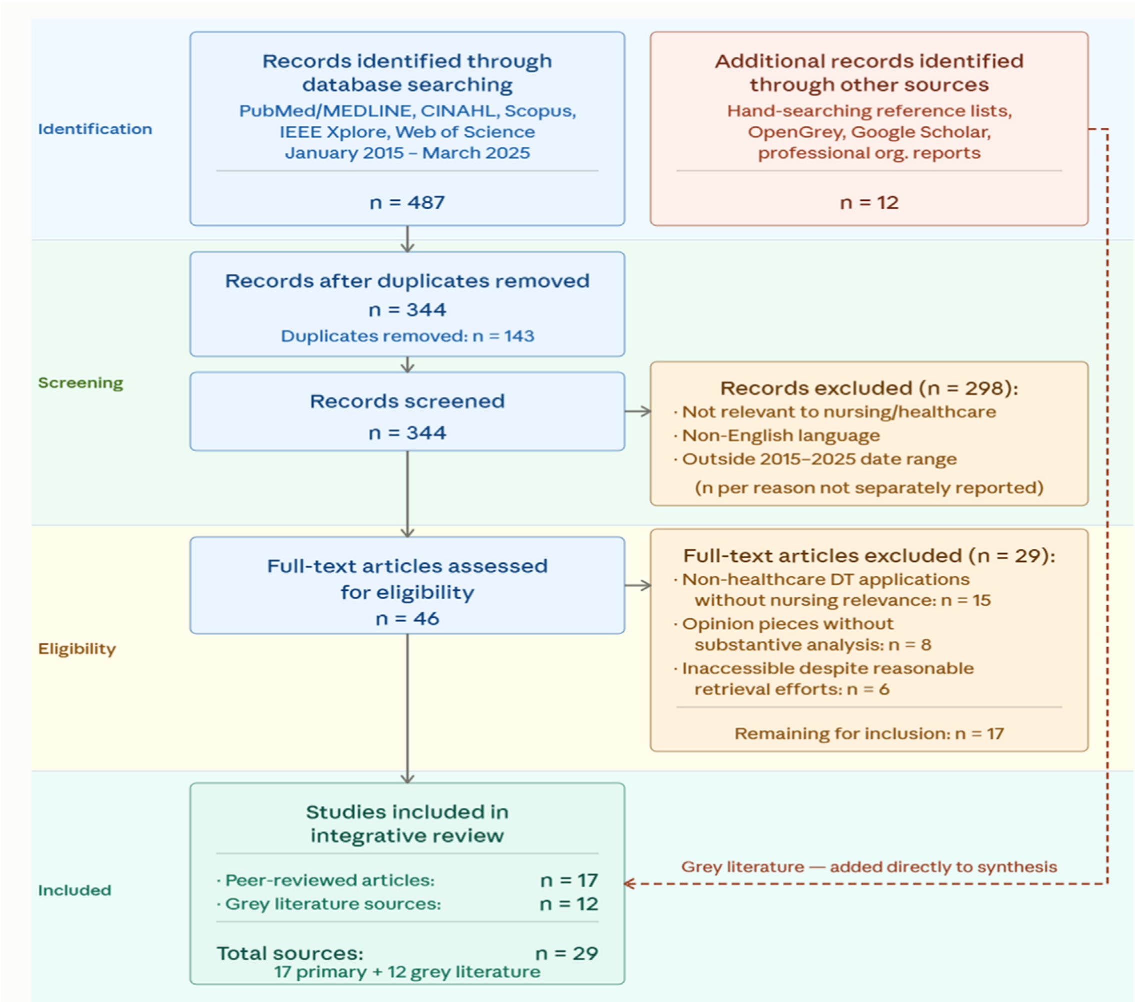

Figure 1. PRISMA flow diagram of selected articles.

tial codes to descriptive units (sentences or passages) relevant to digital twin applications in nursing. Codes were documented in the structured extraction template. In Stage 4b (Data Display), coded extracts were organized into a thematic matrix, grouping related codes across sources to enable visual comparison of patterns. In Stage 4c (Data Comparison), the thematic matrix was interrogated through constant comparative analysis: codes were compared within and across sources, grouped into candidate themes, and iteratively refined through meetings between both reviewers. Candidate themes were merged, disaggregated, or renamed as the analysis evolved. In Stage 4d (Conclusion Drawing and Verification), candidate themes were reviewed against the full dataset to ensure they adequately represented the breadth of included sources and accurately captured the range of evidence. Thematic definitions were finalized and reviewed by all authors.

Five overarching themes emerged from this inductive process: (a) conceptual foundations and definitions of digital twins in healthcare and nursing; (b) specific applications of digital twins across nursing practice domains (patient monitoring, education, workforce, safety, and research); (c) opportunities and benefits associated with digital twin adoption in nursing; (d) challenges and limitations to digital twin implementation; and (e) future directions for research, education, and policy. These five themes directly correspond to the organizational structure of Sections (Conceptual Background) and (Applications of Digital Twin in Nursing, Opportunities and Benefits, Challenges and Limitations, and Future Directions) of this review respectively. It is important to note that the section headings for Sections (Opportunities and Benefits) and (Challenges and Limitations) reflect organizing categories that arose directly from this inductive thematic process and were not determined a priori.

The integrative approach enabled critical examination of how findings from different methodological traditions and disciplinary perspectives converge or diverge, facilitating the development of a comprehensive understanding of digital twin technology's role in nursing. Where findings from empirical sources diverged from conceptual or technical sources, this divergence is noted explicitly in the discussion. Multiple perspectives were actively sought to ensure balanced representation of both opportunities and challenges. Given the heterogeneity of sources, formal meta-analysis was not appropriate; findings are therefore presented narratively with direct attribution to included sources throughout.

Applications of digital twin in nursing

Patient monitoring and predictive care

Digital twin technology offers transformative potential for patient monitoring by creating comprehensive, dynamic virtual patient profiles that continuously integrate data from multiple sources (Awasthi et al., 2025). These sources include bedside monitoring systems, wearable biosensors, laboratory information sys-

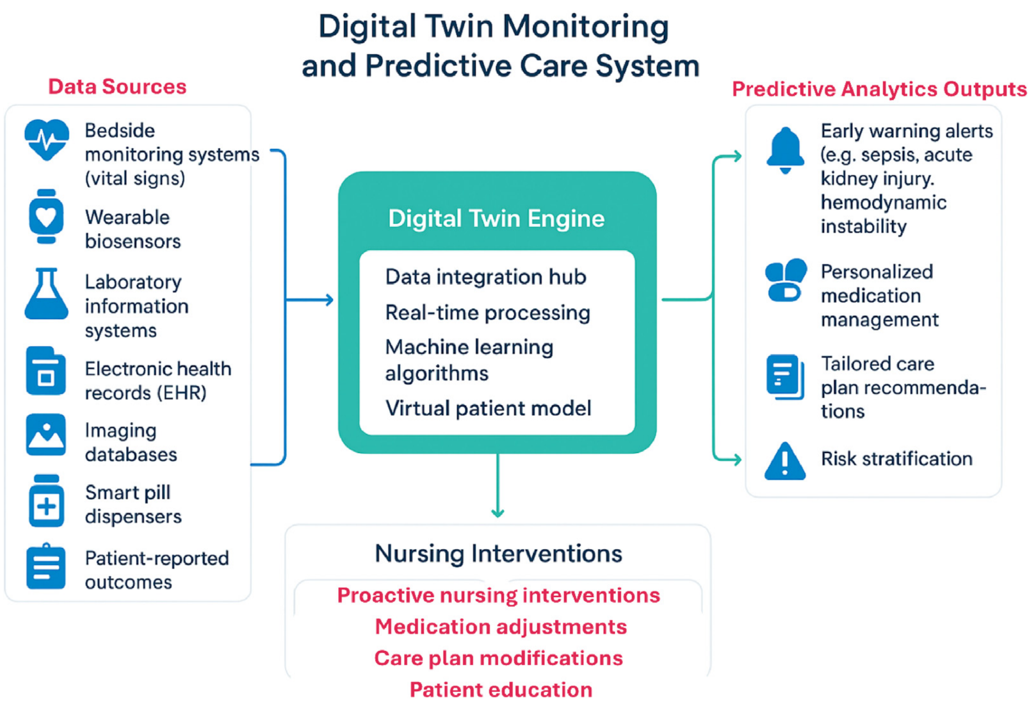

Figure 2. Schematic overview of a digital twin patient monitoring and predictive care System in nursing. Shown are the multiple input data streams including bedside monitoring systems, wearable biosensors, laboratory and imaging databases, smart pill dispensers, patient-reported outcomes, and EHRs integrated by a central digital twin engine.

tems, imaging databases, and electronic health records (Martinez-Velazquez et al., 2019). By synthesizing these diverse data streams, digital twins provide nurses with a holistic, real-time view of patient status that transcends traditional siloed information systems.

It is important to note, however, that while digital twins provide a holistic view of available data, this data-derived overview does not itself constitute a holistic view of the patient. A focus on algorithmically synthesized data carries a risk of privileging quantitative parameters over the full range of physical, relational, and contextual dimensions nurses assess through direct patient contact. Cardona-Morrell et al. (2016) demonstrated through observational research that nurse–patient interaction at the bedside reveals clinically significant information beyond what data monitoring alone captures. Similarly, Wood et al. (2019) found that over-reliance on early warning scores could lead nurses to miss earlier signs of deterioration apparent from holistic physical assessment. Digital twin outputs should therefore be interpreted alongside, not as a substitute for, in-person clinical assessment and interdisciplinary collaboration. One of the most promising applications lies in predictive care, where digital twin models leverage machine learning algorithms to identify patterns indicative of clinical deterioration before traditional warning signs become apparent (Shamout et al., 2019). For example, in intensive care units, a patient's digital twin could continuously analyses trends in vital signs, laboratory values, fluid balance, and medication responses to predict complications such as sepsis, acute kidney injury, or hemodynamic instability hours before clinical manifestation (Cheungpasitporn et al., 2026; Olawade et al., 2025). This early warning capability of digital twin enables proactive nursing interventions that may prevent adverse events and improve patient outcomes (Elkefi & Asan, 2022).

A critical consideration is how digital twin algorithmic outputs are checked and validated before influencing clinical decisions. Robust digital twin systems should incorporate mechanisms to flag when input data is incomplete or of insufficient quality to generate reliable predictions, rather than silently producing outputs based on partial datasets. Validation approaches should include: (a) real-time data completeness checks alerting clinicians when mandatory parameters are absent; (b) confidence intervals displayed alongside predictions; (c) audit trails allowing clinicians to trace recommendations back to source data for manual verification; and (d) prospective clinical validation in diverse populations. Organizations implementing digital twin systems should ensure governance frameworks mandate these validation features as safety requirements (Rajkomar et al., 2018). Digital twins also support personalized medication management, a critical nursing responsibility (Vallée, 2024). By simulating pharmacokinetic and pharmacodynamic responses based on individual patient characteristics, including age, weight, renal function, hepatic function, genetic polymorphisms, and concurrent medications, digital twins can help nurses anticipate therapeutic responses and potential adverse drug reactions (Johnson et al., 2021). This is particularly valuable in populations with complex medication regimens, such as elderly patients with multiple comorbidities.

Furthermore, digital twin technology enables tailored care planning by integrating genomic data, lifestyle factors, social determinants of health, and patient preferences into virtual models (Rasheed et al., 2020). For instance, in chronic disease management, a patient's digital twin could incorporate activity levels from wearable devices, dietary patterns from food diaries, medication adherence data from smart pill dispensers, and psychosocial factors from patient-reported outcome measures to generate personalized self-management recommendations and predict risk of exacerbations (Croatti et al., 2020). As illustrated in Figure 2, digital twin technology enables comprehensive patient monitoring, real-time data integration, and predictive analytics that support proactive nursing interventions and personalized care.

Table 1 summarizes the key applications of digital twins in patient monitoring and predictive care, along with potential nursing benefits and implementation considerations.

Table 1
Digital Twin Applications in Patient Monitoring and Predictive Care.

Application Domain	Digital Twin Function	Nursing Benefits	Data Sources Required	Implementation Considerations
Early deterioration detection (Katsoulakis, 2024; Papachristou, 2024; Gu et al., 2023; Vallée, 2023).	Continuous analysis of multi-parameter trends to predict sepsis, respiratory failure, and cardiac events	Earlier intervention, reduced mortality, and improved nurse confidence in escalation decisions	Vital signs monitors, laboratory systems, EHRs, and fluid balance charts	Alert fatigue management, integration with rapid response systems, and validation in diverse patient populations
Medication management (Gu et al., 2023; Sadée et al., 2025; Zhang et al., 2024).	Simulation of drug responses based on patient-specific pharmacological profiles	Reduced adverse drug events, optimized dosing, enhanced medication safety	Medication administration records, laboratory values, genetic testing, and patient demographics	Interoperability with pharmacy systems, clinician education on interpretation, and regulatory approval for clinical decision support
Chronic disease monitoring (El-Warrak, 2024; Gu et al., 2023; Katsoulakis et al., 2024).	Integration of continuous patient-generated health data with clinical parameters	Proactive management, reduced hospital admissions, enhanced patient engagement	Wearable devices, home monitoring equipment, patient-reported outcomes, and clinical databases	Patient digital literacy, device reliability, data transmission infrastructure, and reimbursement models
Postoperative monitoring (Papachristou, 2024; Park et al., 2025; Gu et al., 2023; Vallée, 2023)	Prediction of surgical complications through continuous assessment of recovery trajectories	Early complication detection, tailored recovery plans, and reduced length of stay	Vital signs, pain scores, mobility data, wound assessments, and laboratory values	Integration with enhanced recovery pathways, staff training, and cost-effectiveness evaluation
Mental health assessment (Gu et al., 2023; Kabir et al., 2025; Sadée et al., 2025).	Analysis of behavioral patterns, sleep, activity, and self-reported mood	Early identification of deterioration, personalized interventions, improved outcomes	Wearable sensors, electronic mood diaries, social interaction data, and clinical assessments	Privacy concerns, ethical considerations, algorithm validation, and integration with mental health services

Nursing workload and workflow optimization

Nursing workforce challenges, including staff shortages, burnout, and high turnover rates, represent significant threats to healthcare quality and safety globally (Aiken et al., 2012). Digital twin technology offers innovative solutions for workload management and workflow optimization by creating virtual models of clinical environments, staffing patterns, patient acuity, and care demands (Karakra et al., 2019).

Digital twin models of hospital wards can simulate various staffing scenarios, predicting how different nurse-to-patient ratios, skill mixes, and shift patterns affect workload distribution, patient outcomes, and nurse wellbeing (Maenhout & Vanhoucke, 2013). These simulations enable nurse managers to make evidence-informed staffing decisions, anticipate periods of high demand, and allocate resources more equitably. For example, a digital twin might predict that a particular ward will experience increased acuity based on planned admissions, scheduled procedures, and historical patterns, enabling proactive adjustments to staffing levels before problems arise.

Workflow optimization represents another valuable application. By tracking nurse movements, task patterns, interruptions, and time allocation across different activities, digital twin systems can identify inefficiencies and bottlenecks in care delivery processes (Hendrich et al., 2008). This information can inform the redesign of ward layouts, streamline documentation systems, and reorganize task allocation to minimize nonvalue-added activities and reduce nurse fatigue. Additionally, digital twins can support predictive workforce planning at organizational and system levels. By modelling factors such as seasonal variation in patient volumes, demographic trends, staff retirement patterns, and training pipeline capacity, healthcare organizations can anticipate future staffing needs and implement proactive recruitment and retention strategies (Nuamah et al., 2020).

Nursing education and training

Simulation-based education has become a cornerstone of nursing curricula, providing safe environments for students to develop clinical skills, critical thinking, and decision-making abilities without risk to actual patients (Cant & Cooper, 2017). Digital twin technology enhances traditional simulation approaches by offering personalized, dynamic, and highly realistic training environments. Unlike static mannequins or standardized scenarios, digital twin patients can adapt in real-time to learner interventions, providing immediate feedback and creating consequences that mirror actual clinical practice (Karakra et al., 2019). For instance, a nursing student managing a digital twin patient experiencing respiratory distress would observe realistic physiological responses to oxygen administration, positioning, or medication responses that adjust based on the student's actions and the virtual patient's underlying condition.

Digital twin technology also enables personalized learning pathways (Arantes, 2024). By tracking individual student performance across multiple simulation scenarios, digital twin systems can identify knowledge gaps, skill deficits, and decision-making patterns, then automatically adjust subsequent training scenarios to address these areas (Padilha et al., 2019). This adaptive approach ensures that each learner receives targeted practice in areas where improvement is needed. Furthermore, digital twins facilitate interprofessional education by creating complex virtual patients that require collaborative management by nursing, medical, pharmacy, and allied health students (Yang et al., 2024). These shared digital twin experiences can enhance teamwork, communication, and understanding of different professional roles and perspectives.

Comparison with standard simulation modalities

Standard simulation modalities in nursing education include low-fidelity mannequins, high-fidelity patient simulators (e.g., SimMan), standardized patient interactions, screen-based virtual simulations, and task trainers focused on specific procedural skills such as venepuncture or urinary catheterization (Cant & Cooper, 2017). These traditional approaches offer valuable learning opportunities but are fundamentally constrained by fixed scenarios, limited physiological realism, and the inability to adapt dynamically to individual learner actions beyond preprogrammed responses. The facilitator-controlled nature of conventional high-fidelity simulation means that physiological changes are manually triggered, reducing ecological validity and limiting the unpredictability that nurses encounter in actual clinical environments.

Digital twin simulation differs from these modalities in several fundamental ways. Whereas high-fidelity mannequins respond according to preset physiological scripts, digital twin patients are driven by computational models that generate physiological responses in real-time based on the learner's specific interventions, the virtual patient's underlying pathophysiology, and evidence-based clinical algorithms (Karanam et al., 2025). This produces a level of individualization and dynamic realism that exceeds what traditional simulators can offer. For example, administering a medication to a digital twin patient with renal impairment would trigger a pharmacokinetically accurate response accounting for altered drug clearance, a degree of specificity that standard mannequins cannot replicate without direct facilitator override. Furthermore, digital twin simulations can draw on actual patient data to create clinically realistic virtual patients that reflect the complexity and heterogeneity of real populations, whereas traditional simulators typically model idealized or standardized patient presentations (Li et al., 2025). This capacity to simulate rare, complex, or high-acuity scenarios that nursing students may not routinely encounter during clinical placements represents a significant pedagogical advantage over conventional simulation approaches.

Technology requirements for digital twin simulation

Deploying digital twin simulation in nursing education requires a robust technological infrastructure that differs substantially from that needed for traditional simulation. Core technology requirements include: (a) high-performance computing infrastructure capable of running validated physiological models in real-time; (b) integration middleware connecting the digital twin engine with monitoring devices, data repositories, and user interfaces; (c) validated computational models of human physiology encompassing cardiovascular, respiratory, renal, neurological, and pharmacological systems; (d) immersive visualization interfaces such as high-resolution screens, virtual reality headsets, or augmented reality overlays; and (e) secure data management platforms supporting both real-time processing and longitudinal tracking of learner performance (Laamarti et al., 2020; Karanam et al., 2025).

Unlike traditional simulation equipment, which can operate as standalone units without network dependency, digital twin systems typically require reliable high-bandwidth network connectivity, cloud or on-premises computing resources, interoperability with existing health information systems, and ongoing technical support for model maintenance and software updates (Liu et al., 2019). This infrastructure dependency introduces operational complexity, procurement considerations, and recurrent costs that differ substantially from conventional simulation acquisition models. Institutions contemplating adoption must therefore conduct comprehensive readiness assessments encompassing IT infrastructure, technical support capacity, and data governance frameworks prior to implementation.

Simulation design and implementation differences

The design and implementation of digital twin simulation scenarios differ from standard simulation in several important respects. Traditional simulation scenarios are authored as branching scripts with defined decision points and preset outcomes, allowing facilitators to control the pace and direction of learning events. By contrast, digital twin simulation scenarios are parameterized models in which learner actions interact continuously with the virtual patient's physiological state, generating emergent outcomes that may not be entirely predictable in advance (Padilha et al., 2019). Facilitators designing digital twin scenarios must therefore possess both advanced clinical expertise and sufficient understanding of the underlying computational models to configure initial patient states, set physiological parameters, and critically evaluate the realism of generated responses.

Implementation also requires substantive adaptation of existing nursing curricula to incorporate digital twin-specific competencies, including data literacy, interpretation of algorithmic outputs, and critical engagement with computational predictions. Debriefing strategies appropriate for data-rich simulation environments must be developed, recognizing that learners may need to interrogate not only their clinical decisions but also the assumptions embedded in the virtual patient model. Faculty development programs are consequently essential to ensure nursing educators can guide learners effectively and critically within these novel platforms (McGonigle & Mastrian, 2024).

Simulation-specific limitations

Despite its considerable potential, digital twin simulation in nursing education carries specific limitations that warrant explicit acknowledgement. First, the computational models underpinning digital twin patients are necessarily simplifications of highly complex biological systems and may not accurately replicate all physiological nuances, particularly in rare diseases, extreme clinical presentations, or conditions characterized by substantial interindividual variability. Rigorous validation of these models against real patient data is resource-intensive and may remain incomplete across diverse patient populations and clinical contexts (Rajkomar et al., 2018).

Second, the high infrastructure requirements place digital twin simulation substantially out of reach for many nursing schools in low- and middle-income countries and smaller institutions in high-income settings, potentially creating new inequities in simulation-based education access. Third, there is a risk that learners may overgeneralize findings from digital twin scenarios to real clinical environments if the limitations of the underlying models are not made sufficiently transparent during the educational experience. Fourth, the immersive focus on physiological and algorithmic data in digital twin simulation may inadequately prepare learners for the relational, communicative, and holistic dimensions of nursing care, which remain irreducible to computational modelling and are central to nursing's professional identity (Yang et al., 2024). Finally, the empirical evidence-base for digital twin simulation's superiority over high-fidelity mannequin simulation in terms of measurable educational outcomes, including clinical competency, knowledge acquisition, and transfer to practice, remains nascent, and robust comparative studies are urgently needed to establish its relative pedagogical value (Karanam et al., 2025).

Enhancing patient safety and quality of care

Patient safety represents a fundamental nursing responsibility and a key indicator of the quality of care. Digital twin technology contributes to safety enhancement through multiple mechanisms, including adverse event prediction, environmental risk modelling, and care protocol optimization (Shamout et al., 2019). In the realm of adverse event prevention, digital twins can predict risks such as falls, pressure injuries, hospital-acquired infections, and medication errors by continuously analyzing patient characteristics, environmental factors, and care processes. Drawing on Hessels et al. (2016), whose cross-sectional observational study across 11 hospital units demonstrated that actual standard precaution adherence was only 62%, markedly below the 94% self-reported by nurses, and that unit-level staffing conditions were the strongest predictor of adherence failure ($r^2 = -0.85$, $p < .01$), with management support and teamwork within units further correlated with specific precaution behaviors including hand hygiene and sharps handling, digital twins can be configured to continuously monitor precisely these organizational and workflow variables, generating proactive alerts when staffing thresholds or safety climate patterns predictive of infection control breakdown are detected. For example, a digital twin might identify a patient at high risk of falls based on factors such as medication profile, cognitive status, mobility limitations, and environmental hazards, and then recommend targeted preventive interventions, including bed alarms, scheduled toileting, or environmental modifications.

Digital twins of healthcare environments enable virtual testing of safety interventions before implementation (Faisal et al., 2025). Nurses can simulate changes to ward layouts, equipment placement, or care protocols to evaluate their impact on patient movement patterns, staff efficiency, and potential hazards (Xuan et al., 2025). This virtual testing approach reduces trial-and-error implementation and accelerates identification of effective safety strategies. Additionally, digital twin technology supports quality improvement initiatives by providing detailed, real-time data on nursing-sensitive quality indicators such as pain management, pressure injury prevalence, catheter-associated infections, and patient satisfaction (Montalvo, 2007). This granular data enables rapid identification of quality issues, targeted interventions, and continuous monitoring of improvement efforts.

Nursing research and evidence generation

Digital twin technology offers researchers powerful new tools for generating evidence and testing interventions without exposing actual patients to experimental risks (Barricelli et al., 2019). Virtual clinical trials using digital twin cohorts can evaluate new nursing protocols, care delivery models, and technologies in simulated environments before proceeding to human studies (Pammi et al., 2025; Ştefănigă et al., 2024). For instance, researchers could create digital twins representing diverse patient populations to test the effectiveness of a new pain management protocol across different ages, conditions, and settings (Liu et al., 2019). This approach enables rapid iteration and refinement of interventions based on simulated outcomes, potentially accelerating translation of research findings into practice.

Digital twins also facilitate the generation of real-world evidence by aggregating and analyzing large-scale datasets from actual patient care (Croatti et al., 2020). These analyses can identify patterns, relationships, and outcomes that inform evidence-based nursing practice, quality improvement initiatives, and policy decisions. Moreover, digital twin platforms can serve as testbeds for evaluating nursing-sensitive outcomes under various scenarios, supporting comparative effectiveness research and health services studies.

Opportunities and benefits of digital twin in nursing

The opportunities and benefits discussed in this section, and the challenges and limitations discussed in the Challenges and Limitations section, were not determined a priori. Rather, they represent thematic categories that emerged inductively from the iterative thematic synthesis described in Section (Data Synthesis and Analysis), in which patterns across the included literature were coded, grouped, and refined through constant comparative analysis. The categories of opportunities/benefits and challenges/limitations represent the two dominant meta-themes consistently identified across the included sources, each containing multiple subthemes that are described below.

The integration of digital twin technology into nursing practice, education, and research presents numerous opportunities to address longstanding challenges and enhance care delivery. These opportunities span individual patient care, workforce sustainability, educational effectiveness, and research advancement (Venkatesh et al., 2022). Personalized and Precision Nursing Care represents perhaps the most transformative opportunity. Digital twins enable nurses to deliver truly individualized care by providing comprehensive, dynamic patient profiles that integrate biological, psychological, social, and environmental factors (Rasheed et al., 2020). This holistic view supports clinical decision-making that accounts for each patient's unique characteristics, preferences, and circumstances, moving beyond standardized, protocol-driven approaches to genuinely person-centered care.

Enhanced Clinical Decision Support emerges from the digital twin's ability to synthesize complex, multidimensional data into actionable insights. Nurses, who often manage multiple patients with competing priorities, can benefit from digital twin systems that prioritize alerts, highlight concerning trends, and recommend evidence-based interventions (Shamout et al., 2019). This support is particularly valuable for novice nurses who are still developing pattern recognition and clinical judgement skills.

Proactive Rather Than Reactive Care becomes possible through a digital twin's predictive capabilities. By identifying deterioration risks, predicting complications, and anticipating care needs, digital twins enable nurses to intervene before problems escalate, potentially preventing adverse events, reducing the need for emergency responses, and improving patient outcomes (Gu et al., 2023). This shift from reactive firefighting to proactive prevention can reduce nurse stress and enhance job satisfaction.

Workforce Optimization and Sustainability addresses critical staffing challenges. Digital twin-enabled workload management systems can distribute assignments more equitably, accurately predict staffing needs, and reduce burnout by preventing chronic understaffing and overwork (Abd Elaziz et al., 2024). Over time, these improvements may enhance nurse retention, reduce turnover costs, and improve workforce sustainability.

Accelerated Learning and Competency Development in nursing education offers opportunities to expose students to rare or complex clinical scenarios that they might not encounter during traditional clinical placements (Cant & Cooper, 2017). Digital twin simulations offer safe and repeatable practice opportunities that build confidence and competence before students assume full patient care responsibilities.

Table 2 summarizes the key opportunities and benefits of digital twin technology across different domains of nursing practice.

Challenges and limitations

Despite its considerable promise, digital twin implementation in nursing faces significant challenges spanning technical, ethical, legal, organizational, and workforce-related domains. These barriers must be addressed systematically to enable responsible and effective adoption (Bruynseels et al., 2018).

Technical and infrastructure challenges

Data Integration and Interoperability represent a fundamental technical barrier. Healthcare organizations typically operate multiple disparate information systems, such as EHRs, laboratory information systems, radiology systems, pharmacy systems, and various monitoring devices, that often cannot communicate effectively (Sensmeier, 2017). Creating functional digital twins requires seamless integration of data from all these sources in real-time, which demands significant investment in interface development, data standardization, and infrastructure upgrading.

Data Quality and Completeness issues pose additional challenges. Digital twin models are only as reliable as the data they receive (Wright & Davidson, 2020). Missing data, measurement errors, documentation inconsistencies, and temporal delays in data entry can all compromise the accuracy of digital twins (Ronquillo et al., 2021). Nursing documentation, although rich in qualitative observations, may lack the structured format required for computational analysis, necessitating the implementation of

Table 2
Opportunities and Benefits of Digital Twin in Nursing Practice.

Benefit Category	Specific Opportunities	Impact on Nursing Practice	Impact on Patient Outcomes	Impact on the Healthcare System
Personalised care (Zhang et al., 2024; Mollica et al., 2024; Gu et al., 2023)	Individualised care plans, tailored interventions, patient-specific predictions	Enhanced clinical decision-making, increased nurse satisfaction with care delivery, improved care continuity	Better symptom management, increased patient engagement, improved quality of life, reduced adverse events	Reduced hospital readmissions, optimised resource utilization, improved cost-effectiveness
Predictive capabilities (Repetto et al., 2025; Kabir et al., 2025)	Early warning systems, complication prediction, deterioration alerts	Proactive interventions, reduced emergency responses, decreased stress from unexpected events	Prevention of adverse events, reduced mortality and morbidity, shorter hospital stays	Lower costs from prevented complications, reduced intensive care admissions, improved throughput
Workflow efficiency (Meijer et al., 2023; Kabir et al., 2025)	Optimised task allocation, balanced workloads, streamlined processes	Reduced time on documentation, more time for direct patient care, decreased fatigue	Increased nurse presence at bedside, improved nurse-patient interactions, enhanced care coordination	Improved productivity, reduced overtime costs, better staff retention
Enhanced education (Karanam et al., 2025; Li et al., 2025)	Realistic simulations, adaptive learning, unlimited practice opportunities	Accelerated skill development, improved critical thinking, increased confidence	Better prepared nurses, reduced errors from inexperience, improved care quality	Reduced training costs, faster onboarding, decreased supervision requirements
Research advancement (Wu et al., 2024; Lim et al., 2025)	Virtual trials, large-scale data analysis, rapid hypothesis testing	Evidence generation for nursing interventions, validation of practice innovations	Implementation of evidence-based interventions, continuous care improvement	Accelerated translation of research to practice, reduced research costs

natural language processing capabilities or changes to documentation practices.

Computational Demands for real-time modelling and simulation can be substantial, particularly when creating digital twins for multiple patients simultaneously or modelling complex physiological systems (Liu et al., 2019). Many healthcare organizations, especially in resource-limited settings, often lack the necessary computing infrastructure, technical expertise, and financial resources to implement and maintain digital twin systems.

Algorithm Validation and Reliability concerns arise because many digital twin systems rely on machine learning models trained on specific datasets that may not represent all patient populations (Rajkomar et al., 2018). Algorithms developed using data from predominantly young, urban populations may perform poorly when applied to elderly, rural, or ethnically diverse patient groups. Ensuring that digital twin models are validated across diverse populations and clinical contexts requires extensive testing and refinement to ensure accuracy and reliability.

Ethical and legal challenges

Patient Privacy and Data Security represent paramount concerns. Digital twins aggregate vast amounts of sensitive health information, making them attractive targets for cyberattacks and data breaches (Laamarti et al., 2020). Moreover, the continuous data collection required for digital twin functionality raises questions about surveillance, patient autonomy, and the extent to which individuals can truly provide informed consent for uses of their data that may not yet be fully defined.

Informed Consent and Ownership issues become complex when considering digital twins. Who owns a patient's digital twin? Can patients request deletion of their digital twin? How should consent be obtained for using digital twin data in research or quality improvement activities? These questions lack clear legal frameworks in most jurisdictions. In the United Kingdom, the Data Protection Act 2018 and UK GDPR provide health data governance frameworks but do not specifically address digital twin ownership or deletion rights. Within the EU, GDPR offers some protections but application to continuously updated predictive AI models remains legally untested. In the United States, HIPAA regulations were not designed for real-time AI-driven patient representations, leaving significant regulatory gaps. In low- and middle-income country contexts, data protection legislation is often less developed. Nursing organizations and policymakers must therefore engage proactively with these governance challenges (Bruynseels et al., 2018).

Algorithmic Bias and Health Equity concerns emerge from recognition that AI systems can perpetuate or amplify existing healthcare disparities (Rajkomar et al., 2018). Suppose digital twin models are trained predominantly on data from well-resourced hospitals serving privileged populations. In that case, they may provide inferior predictions and recommendations for marginalized communities, potentially widening rather than narrowing health equity gaps. A related and equally important concern pertains to international algorithmic validity. An algorithm trained and validated in one country cannot be assumed to perform equivalently when deployed in other geographical or healthcare contexts. Clinical norms, disease prevalence, population demographics, documentation practices, and nursing workflows vary substantially between countries and healthcare systems. For example, early warning score thresholds validated in UK NHS populations may not generalize to Nigerian, Brazilian, or Southeast Asian contexts where baseline physiological parameters, prevalent comorbidities, and patient acuity distributions differ. Researchers and implementers must resist the assumption that algorithms proven effective in high-income country settings are universally applicable and should require contextual revalidation prior to deployment in different national or institutional environments. This concern is particularly salient for nursing, where staffing ratios, skill mix, and the burden of documentation that feeds digital twin models vary enormously across international settings.

Accountability and Liability questions arise when digital twin systems make recommendations that influence clinical decisions. If a nurse follows a digital twin recommendation that leads to patient harm, who bears responsibility: the nurse, the software developer, the healthcare organization, or some combination thereof? (Char et al., 2018). These liability concerns may create hesitancy among nurses to trust and act upon digital twin insights.

Workforce and organizational challenges

Limited Awareness and Digital Literacy among nurses represent a significant barrier. Many practicing nurses received their education before the widespread adoption of health informatics training and may feel uncomfortable with advanced technologies (McGonigle & Mastrian, 2024). Building digital twin literacy requires substantial investment in continuing education, training programs, and ongoing support.

Resistance to Change is a well-documented phenomenon in healthcare organizations. Nurses may perceive digital twin systems as a threat to clinical autonomy, an expression of mistrust in their judgment, or an additional burden in already overwhelming workloads (Booth et al., 2021). Overcoming this resistance requires thoughtful change management, meaningful nurse engagement in technology design and implementation, and demonstration of tangible benefits.

Risk of Skill Erosion arises from concerns that over-reliance on digital twin recommendations could diminish nurses' clinical reasoning abilities and pattern recognition skills (Karakra et al., 2019). If nurses become dependent on algorithmic alerts and predictions, they may lose the ability to recognize deterioration through traditional observation and assessment, potentially creating vulnerability when technology fails.

Resource Constraints affect implementation in multiple ways. The financial costs of digital twin systems, including software licensing, hardware infrastructure, training, and ongoing maintenance, can be prohibitive, particularly for smaller healthcare organizations or those in low-resource settings (Nuamah et al., 2020). Additionally, the time required for nurses to learn new systems, adjust workflows, and provide feedback during implementation represents a scarce resource in already time-pressured environments.

Future directions

The successful integration of digital twin technology into nursing practice, education, and research requires coordinated efforts across multiple domains. Several key priorities emerge from this review as essential for advancing the field responsibly and effectively.

Interdisciplinary Collaboration represents a foundational requirement for the development and implementation of digital twins. Nurses must work alongside computer scientists, data scientists, engineers, physicians, ethicists, policymakers, and patients to codesign systems that are clinically meaningful, technically robust, ethically sound, and user-centered (Karakra et al., 2019). This collaboration should extend beyond technology development to include joint research initiatives, shared governance structures, and integrated implementation teams.

Integration into Nursing Education must occur at all levels to prepare the nursing workforce for digital twin-enabled practice. Undergraduate nursing curricula should incorporate foundational concepts in health informatics, data literacy, and digital twin technology (McGonigle & Mastrian, 2024). Simulation experiences using digital twin platforms can offer students realistic and adaptive learning opportunities. Continuing professional development programs must offer practicing nurses opportunities to develop competencies in using digital twin tools effectively and critically.

Pilot Studies and Clinical Trials are urgently needed to generate empirical evidence on the effectiveness, usability, and impact of digital twins in real nursing contexts. These studies should employ rigorous methodologies, include diverse patient populations and clinical settings, and measure outcomes across multiple domains, including patient safety, care quality, nurse satisfaction, workload, and cost-effectiveness (Liu et al., 2019). Comparative studies examining digital twin approaches versus traditional care can help identify which applications deliver the greatest value.

The development of Regulatory Frameworks that balance innovation with patient safety and ethical considerations is essential. Professional nursing organizations, regulatory agencies, and policymakers must collaborate to establish standards for digital twin validation, approval processes, liability frameworks, and practice guidelines (Char et al., 2018). These frameworks should be flexible enough to accommodate technological evolution while providing sufficient protection for patients and practitioners.

Equity-focused implementation must be prioritized to ensure digital twin technology does not exacerbate existing health disparities. This includes developing and validating algorithms using diverse datasets, ensuring digital twin tools are accessible in resource-limited settings through affordable and scalable solutions, addressing digital literacy barriers, and monitoring implementation for unintended discriminatory effects (Rajkomar et al., 2018). Deliberate efforts to include marginalized communities in digital twin development and deployment are essential.

Ethical Governance Structures should be established to oversee the development and use of digital twins. These structures might include ethics committees with expertise in technology, data science, and nursing; patient and public involvement mechanisms; and ongoing ethical review processes that adapt to emerging issues (Bruynseels et al., 2018). Transparent reporting of digital twin capabilities, limitations, and evidence-based information should be standard practice.

Standardization Efforts to enable interoperability, data sharing, and generalization of digital twin models across institutions would accelerate progress. Development of common data models, terminology standards, and technical specifications for healthcare digital twins could facilitate collaboration and reduce redundant development efforts (Gu et al., 2023). Figure 3 provides a visual roadmap of strategic priorities required for the responsible and effective integration of digital twin technology into nursing, spanning interdisciplinary collaboration, education, research, ethics, regulation, standards, and equity-focused implementation.

Limitations of the review

This integrative review has several limitations that warrant acknowledgement. First, the emerging nature of the field means that much of the literature is conceptual rather than empirical. While this review synthesizes current thinking and identifies potential applications, robust evidence from clinical trials and implementation studies remains limited. Conclusions regarding the effectiveness and impact of digital twins should therefore be considered preliminary, pending the accumulation of empirical evidence.

Second, while integrative reviews are designed to incorporate diverse methodological literature, this breadth introduces inherent heterogeneity that precludes quantitative synthesis or meta-analysis. The inclusion of empirical studies, conceptual papers, grey literature, and technical documents means that findings represent varied levels of evidence rigor. Although we considered source credibility throughout the synthesis process, formal quality appraisal using standardized tools was not conducted, which is a recognized limitation of integrative review methodology. Different reviewers might have weighted or interpreted sources differently, introducing potential subjective bias in the synthesis.

Third, limited nursing-specific literature required extrapolation from broader healthcare digital twin literature. Many studies examining digital twin applications in medicine, surgery, or general healthcare do not explicitly discuss nursing implications. This review necessarily involved inference regarding how findings from these studies might translate to nursing contexts. These inferences, while informed by nursing expertise, remain speculative until confirmed through nursing-focused research.

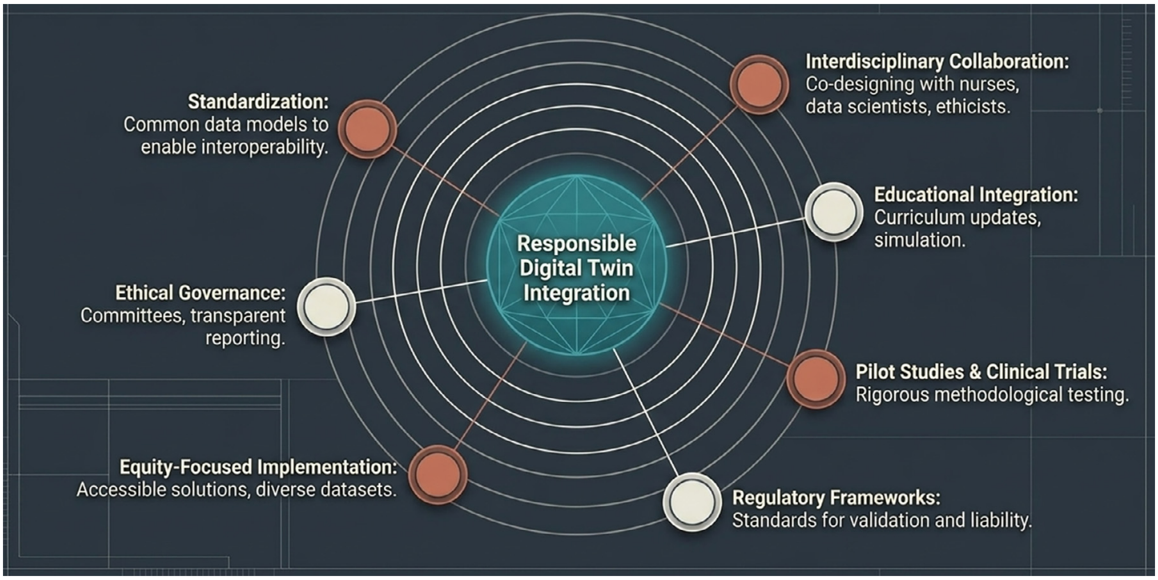

Figure 3. Strategic roadmap for future directions in the adoption of digital twin technology in nursing. Central to the diagram is responsible digital twin integration, surrounded by key thematic pillars: interdisciplinary collaboration, educational integration, pilot studies and clinical trials, regulatory frameworks, equity-focused implementation, ethical governance, and standardization.

Fourth, the rapid pace of technological development means this review may become outdated relatively quickly. Digital twin capabilities are evolving rapidly, and new applications, tools, and evidence may emerge shortly after publication. The literature search was conducted through March 2025, and developments occurring subsequently are not captured.

Fifth, geographic and linguistic limitations may affect comprehensiveness. The review included only English-language publications, potentially missing relevant work published in other languages. Additionally, most included literature originates from high-income countries with advanced healthcare infrastructures, which limits insights into digital twin applications in resource-limited settings or diverse healthcare systems.

Sixth, grey literature coverage, while included, may be incomplete. Many digital twin implementations in healthcare are commercially driven, and full details may be proprietary or unpublished. Conference presentations, pilot projects, and implementation experiences that have not been formally published are difficult to identify and access systematically, even with the broad search approach characteristic of integrative reviews.

Finally, the interdisciplinary nature of digital twin technology means relevant literature spans multiple domains, including computer science, engineering, medicine, and nursing. Despite comprehensive searching across multiple databases, some relevant publications may have been missed, particularly those in highly specialized technical literature that might not be indexed in healthcare databases.

These limitations suggest that findings should be interpreted cautiously and that ongoing systematic research is needed to establish evidence-based guidelines for digital twin implementation in nursing practice. Future systematic reviews focusing on specific digital twin applications with more homogeneous evidence bases would complement this integrative synthesis.

Conclusion

Digital twin technology represents a paradigm shift in healthcare delivery, offering transformative potential for nursing practice, education, and research. By providing real-time, predictive, and personalized insights, digital twins can enable nurses to deliver safer, more effective, and more efficient care while simultaneously addressing critical workforce challenges, such as burnout, staffing shortages, and workload management.

This narrative review has identified five key application domains where digital twins demonstrate particular promise for nursing: patient monitoring and predictive care, workload and workflow optimization, education and training, patient safety enhancement, and research and evidence generation. Across these domains, digital twins offer opportunities to shift nursing practice from reactive to proactive, from standardized to personalized, and from intuition-based to data-informed decision-making. However, realizing this potential requires systematic attention to significant challenges spanning technical infrastructure, data quality and interoperability, ethical considerations including privacy and algorithmic bias, regulatory frameworks, and workforce development. The successful integration of digital twin technology into nursing will depend not only on technology alone but also on thoughtful, collaborative approaches that center on nursing expertise, patient safety, and ethical principles.

As nursing continues to evolve in the digital age, embracing technologies like digital twins may be essential to achieving more resilient, sustainable, and patient-centered healthcare systems. The path forward requires interdisciplinary collaboration, investment in education and infrastructure, rigorous research to build the evidence base, and development of governance frameworks that ensure responsible innovation. With these elements in place, digital twin technology can help fulfil nursing's fundamental commitment to providing the highest quality care to all individuals, families, and communities.

Ethics statement

It is a narrative review and did not involve human participants, patient data, or primary data collection requiring institutional ethical approval.

Conflicts of Interest

None.

CRediT authorship contribution statement

Aanuoluwapo Clement David-Olawade: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Sandra Chinaza Fidelis:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Mayowa Racheal Popoola:** Writing – review & editing, Writing – original draft, Project administration, Methodology. **Adewoyin A. Osonuga:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Eghosasere Egbon:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **David B. Olawade:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation.

References

Abd Elaziz, M., Al-qaness, M. A., Dahou, A., Al-Betar, M. A., Mohamed, M. M., El-Shinawi, M., & Ewees, A. A. (2024). Digital twins in healthcare: Applications, technologies, simulations, and future trends. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 14*(6), Article e1559.

Adetunji, O., & Odili, N. O. A. (2024). Advanced digital-twin odeling for predictive monitoring of postoperative cardiac patients using wearables and EHR data. *GSC Biological and Pharmaceutical Sciences, 27*(1), 295–314.

Aiken, L. H., Sermeus, W., Van den Heede, K., Sloane, D. M., Busse, R., McKee, M., & Kutney-Lee, A. (2012). Patient safety, satisfaction, and quality of hospital care: Cross sectional surveys of nurses and patients in 12 countries in Europe and the United States. *British Medical Journal (Clinical Research Edition), 344*, Article e1717.

Alrehaili, M. M., Alrashedi, G. S. O., Alshammary, G. R. S., Alshammari, N. R., Alshammari, F. K., Dagreri, W. A., & Alenezi, F. A. (2024). Caring under pressure: Unraveling the crisis of nursing workload and stress in modern healthcare. *Journal of International Crisis and Risk Communication Research, 7*(S4), 7.

Arantes, J. (2024). Digital twins and the terminology of "personalization" or "personalized learning" in educational policy: A discussion paper. *Policy Futures in Education, 22*(4), 524–543.

Armeni, P., Polat, I., De Rossi, L. M., Diaferia, L., Meregalli, S., & Gatti, A. (2022). Digital twins in healthcare: Is it the beginning of a new era of evidence-based medicine? A critical review. *Journal of Personalized Medicine, 12*(8), 1255.

Awasthi, M., Raghuvanshi, C. S., Dudhagara, C., & Awasthi, A. (2025). Exploring virtual smart healthcare trends using digital twins. In *Digital twins for smart cities and villages* (pp. 377–406). Elsevier.

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access: Practical Innovations, Open Solutions, 7*, 167653–167671.

Booth, R. G., Strudwick, G., McBride, S., O'Connor, S., & López, A. L. S. (2021). How the nursing profession should adapt for a digital future. *British Medical Journal (Clinical Research Edition), 373*, Article n1190.

Bruynseels, K., Santoni de Sio, F., & Van den Hoven, J. (2018). Digital twins in health care: Ethical implications of an emerging engineering paradigm. *Frontiers in Genetics, 9*, 31.

Cant, R. P., & Cooper, S. J. (2017). Use of simulation-based learning in undergraduate nurse education: An umbrella systematic review. *Nurse Education Today, 49*, 63–71.

Cardona-Morrell, M., Prgomet, M., Lake, R., Nicholson, M., Harrison, R., Long, J., … Hillman, K. (2016). Vital signs monitoring and nurse–patient interaction: A qualitative observational study of hospital practice. *International Journal of Nursing Studies, 56*, 9–16.

Char, D. S., Shah, N. H., & Magnus, D. (2018). Implementing machine learning in health care—Addressing ethical challenges. *The New England Journal of Medicine, 378*(11), 981.

Cheungpasitporn, W., Athavale, A., Ghazi, L., Kashani, K. B., Colicchio, T., Koyner, J. L., & Neyra, J. A. (2026). Transforming nephrology through artificial intelligence: A state-of-the-art roadmap for clinical integration. *Clinical Kidney Journal, 19*(2), sfag004.

Croatti, A., Gabellini, M., Montagna, S., & Ricci, A. (2020). On the integration of agents and digital twins in healthcare. *Journal of Medical Systems, 44*(9), 161.

Curley, M. A. (2007). *Synergy: The unique relationship between nurses and patients*. Sigma Theta Tau International https://cir.nii.ac.jp/crid/1971149384848248768.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly, 13*(3), 319–340.

El Saddik, A., Laamarti, F., & Alja'Afreh, M. (2021). The potential of digital twins. *IEEE Instrumentation & Measurement Magazine, 24*(3), 36–41.

Elkefi, S., & Asan, O. (2022). Digital twins for managing health care systems: Rapid literature review. *Journal of Medical Internet Research, 24*(8), Article e37641.

El-Warrak, L., & de Farias, C. M. (2024). The state of the art of digital twins in health—A quick review of the literature. *Computers, 13*(9), 228.

Faisal, S. M., Ishrat, M., & Khan, W. (2025). Digital twins in healthcare: Revolutionizing patient care and medical operations. In *Digital twins for smart cities and urban planning* (pp. 69–89). CRC Press.

Grieves, M., & Vickers, J. (2016). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary perspectives on complex systems: New findings and approaches* (pp. 85–113). Springer International Publishing.

Gu, D., Cao, Y., Zhou, X., Zan, Y., Zhang, X., Xie, J., & Yu, M. (2023). Digital twins in the field of nursing: A literature review. *CIN: Computers, Informatics, Nursing, 43*(10), 10–1097.

Hendrich, A., Chow, M. P., Skierczynski, B. A., & Lu, Z. (2008). A 36-hospital time and motion study: How do medical-surgical nurses spend their time? *The Permanente Journal, 12*(3), 25.

Hessels, A. J., Genovese-Schek, V., Agarwal, M., Wurmser, T., & Larson, E. L. (2016). Relationship between patient safety climate and adherence to standard precautions. *American Journal of Infection Control, 44*(10), 1128–1132.

Holden, R. J., & Karsh, B. T. (2010). The technology acceptance model: Its past and its future in health care. *Journal of Biomedical Informatics, 43*(1), 159–172.

Johnson, K. B., Wei, W. Q., Weeraratne, D., Frisse, M. E., Misulis, K., Rhee, K., & Snowdon, J. L. (2021). Precision medicine, AI, and the future of personalized health care. *Clinical and Translational Science, 14*(1), 86–93.

Kabir, M. R., Shishir, F. S., Shomaji, S., & Ray, S. (2025). Digital twins in healthcare IoT: A systematic review. *High-Confidence Computing, 5*(3), Article 100340.

Karakra, A., Fontanili, F., Lamine, E., & Lamothe, J. (2019). HospiT'Win: A predictive simulation-based digital twin for patients pathways in hospital. In *2019 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI)* (pp. 1–4). IEEE.

Karanam, S. A. K., & Hartman, N. W. (2025). A systematic review of digital twin (DT) and virtual learning environments (VLE) for smart manufacturing education. *Manufacturing Letters, 44*, 1597–1608.

Katsoulakis, E., Wang, Q., Wu, H., Shahriyari, L., Fletcher, R., Liu, J., & Deng, J. (2024). Digital twins for health: A scoping review. *NPJ Digital Medicine, 7*(1), 77.

Laamarti, F., Badawi, H. F., Ding, Y., Arafsha, F., Hafidh, B., & El Saddik, A. (2020). An ISO/IEEE 11073 standardized digital twin framework for health and well-being in smart cities. *IEEE Access: Practical Innovations, Open Solutions, 8*, 105950–105961.

Labrague, L. J., & Al Harrasi, M. (2025). Nursing students' perceptions of artificial intelligence (AI) using the technology acceptance model: A systematic review. *Teaching and Learning in Nursing, 20*(3), 274–282.

Legris, P., Ingham, J., & Collerette, P. (2003). Why do people use information technology? A critical review of the technology acceptance model. *Information & Management, 40*(3), 191–204.

Li, Q., Duan, H., Zhou, X., Sun, X., Tao, L., & Lu, X. (2025). The use of metaverse in medical education: A systematic review. *Clinical Medicine, 25*(3), Article 100315.

Lim, Y., & Kim, E. M. (2025). Structural topic modeling analysis of digital twin study in healthcare. In *MEDINFO 2025—Healthcare smart× medicine deep* (pp. 1852–1853). IOS Press.

Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., & Deen, M. J. (2019). A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access: Practical Innovations, Open Solutions, 7*, 49088–49101.

Maenhout, B., & Vanhoucke, M. (2013). An integrated nurse staffing and scheduling analysis for longer-term nursing staff allocation problems. *Omega, 41*(2), 485–499.

Martinez-Velazquez, R., Gamez, R., & El Saddik, A. (2019). Cardio twin: A digital twin of the human heart running on the edge. In *2019 IEEE International Symposium on Medical Measurements and Applications (MeMeA)* (pp. 1–6). IEEE.

McGonigle, D., & Mastrian, K. (2024). *Nursing informatics and the foundation of knowledge*. Jones & Bartlett Learning.

Meijer, C., Uh, H. W., & El Bouhaddani, S. (2023). Digital twins in healthcare: Methodological challenges and opportunities. *Journal of Personalized Medicine, 13*(10), 1522.

Mollica, L., Leli, C., Sottotetti, F., Quaglini, S., Locati, L. D., & Marceglia, S. (2024). Digital twins: A new paradigm in oncology in the era of big data. *ESMO Real World Data and Digital Oncology, 5*, Article 100056.

Montalvo, I. (2007). The national database of nursing quality indicators (NDNQI). *Online Journal of Issues in Nursing, 12*(3), 13. Available from https://research.ebsco.com/plink/41ec2b16-74f8-3028-9ec4-29085b8f143a.

Nepomuceno, A., Kim, I., Cao, C., & Schultz, C. (2024). Immersive digital-twin simulation-driven nursing education. In *IISE Annual Conference Proceedings* (pp. 1–6). Institute of Industrial and Systems Engineers (IISE).

Nuamah, J., Mehta, R., & Sasangohar, F. (2020). Technologies for opioid use disorder management: Mobile app search and scoping review. *JMIR mHealth and uHealth, 8*(6), Article e15752.

Olawade, D. B., Ighodaro, O., Erhieyovwe, E. O., Hankamo, N. E., Hamza, I. T., & Analikwu, C. C. (2025). The role of digital twin technology in modern emergency care. *International Journal of Medical Informatics, 208*(2026), 106229.

Padilha, J. M., Machado, P. P., Ribeiro, A., Ramos, J., & Costa, P. (2019). Clinical virtual simulation in nursing education: Randomized controlled trial. *Journal of Medical Internet Research, 21*(3), Article e11529.

Pammi, M., Shah, P. S., Yang, L. K., Hagan, J., Aghaeepour, N., & Neu, J. (2025). Digital twins, synthetic patient data, and in-silico trials: Can they empower paediatric clinical trials? *The Lancet Digital Health, 7*(5), 100851.

Papachristou, K., Katsakiori, P. F., Papadimitroulas, P., Strigari, L., & Kagadis, G. C. (2024). Digital twins' advancements and applications in healthcare, towards precision medicine. *Journal of Personalized Medicine, 14*(11), 1101.

Park, J., Park, E., Lee, D., Kang, S., Lee, T., Hong, H., & Lee, U. (2025). Human digital twins for pervasive healthcare: A scoping review. *Health Informatics Journal, 31*(4), Article 14604582251392455.

Rajkomar, A., Hardt, M., Howell, M. D., Corrado, G., & Chin, M. H. (2018). Ensuring fairness in machine learning to advance health equity. *Annals of Internal Medicine, 169*(12), 866–872.

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access: Practical Innovations, Open Solutions, 8*, 21980–22012.
Repetto, M., Colapinto, C., Jayaraman, R., Appio, F., & La Torre, D. (2025). Blockchain-enabled predictive digital twin approach for healthcare: Enhancing accuracy and performance with federated learning. *International Journal of Production Economics, 294*(2026), 109768.
Ronquillo, C. E., Peltonen, L. M., Pruinelli, L., Chu, C. H., Bakken, S., Beduschi, A., & Topaz, M. (2021). Artificial intelligence in nursing: Priorities and opportunities from an international invitational think-tank of the nursing and artificial intelligence leadership collaborative. *Journal of Advanced Nursing, 77*(9), 3707–3717.
Sadée, C., Testa, S., Barba, T., Hartmann, K., Schuessler, M., Thieme, A., & Gevaert, O. (2025). Medical digital twins: Enabling precision medicine and medical artificial intelligence. *The Lancet Digital Health, 7*(7), 100864.
Sensmeier, J. (2017). Harnessing the power of artificial intelligence. *Nursing Management, 48*(11), 14–19.
Shamout, F. E., Zhu, T., Sharma, P., Watkinson, P. J., & Clifton, D. A. (2019). Deep interpretable early warning system for the detection of clinical deterioration. *IEEE Journal of Biomedical and Health Informatics, 24*(2), 437–446.
Ştefănigă, S. A., Cordoş, A. A., Ivascu, T., Feier, C. V. I., Muntean, C., Stupinean, C. V., & Bolboacă, S. D. (2024). Advancing precision oncology with digital and virtual twins: A scoping review. *Cancers, 16*(22), 3817.
Vallée, A. (2023). Digital twin for healthcare systems. *Frontiers in Digital Health, 5*, Article 1253050.
Vallée, A. (2024). Envisioning the future of personalized medicine: Role and realities of digital twins. *Journal of Medical Internet Research, 26*, Article e50204.
Venkatesh, K. P., Raza, M. M., & Kvedar, J. C. (2022). Health digital twins as tools for precision medicine: Considerations for computation, implementation, and regulation. *NPJ Digital Medicine, 5*(1), 150.
Whittemore, R., & Knafl, K. (2005). The integrative review: Updated methodology. *Journal of Advanced Nursing, 52*(5), 546–553.
Wood, C., Chaboyer, W., & Carr, P. (2019). How do nurses use early warning scoring systems to detect and act on patient deterioration to ensure patient safety? A scoping review. *International Journal of Nursing Studies, 94*, 166–178.
Wright, L., & Davidson, S. (2020). How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences, 7*(1), 13.
Wu, J., & Koelzer, V. H. (2024). Towards generative digital twins in biomedical research. *Computational and Structural Biotechnology Journal, 23*, 3481–3488.
Xuan, X., Wu, Q., Yang, L., Cao, W., Zhang, Z., & Zheng, Y. (2025). Interaction of nursing efficiency and spatial design in different departments: An agent-based modeling approach. *Frontiers of Architectural Research, 15*(1), 1–23.
Yang, W. X., Shen, S. Y., Yang, D. C., Yu, S. Y., Yao, Z. W., & Cao, S. H. (2024). Digital twin applications in medical education: A scoping review. *Educational Science and Management, 2*(4), 188–196.
Yuanyuan, W., Mengxin, X., Yuan, M., Jiaqi, H., Feng, L., Yiying, W., Min, T., Yingying, D., Zhirun, D., Rui, L., & Juan, N. (2026). The impact of innovativeness on Chinese nurses' attitudes toward artificial intelligence: A cross-sectional study based on the technology acceptance model. *BMC Nursing, 25*, 231.
Zhang, K., Zhou, H. Y., Baptista-Hon, D. T., Gao, Y., Liu, X., Oermann, E., & Wu, J. (2024). Concepts and applications of digital twins in healthcare and medicine. *Patterns, 5*(8), 101028.