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(REVIEW ARTICLE)

# Digital twins and AI for end-to-end sustainable pharmaceutical supply chain management

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## Abstract

Digital Twin (DT) and Artificial Intelligence (AI) technologies rapidly transform the pharmaceutical industry by enabling intelligent, data-driven systems across manufacturing, supply chain logistics, sustainability initiatives, and personalized medicine. This review synthesizes findings from 29 peer-reviewed studies published between 2020 and 2024, highlighting the capabilities of DTs to optimize processes, enhance decision-making, and support regulatory compliance. The analysis categorizes DT applications into four core domains—manufacturing, logistics, sustainability, and clinical care—while identifying emerging trends, research gaps, and integration challenges. The discussion covers key enablers such as IoT, machine learning, and simulation platforms, along with critical limitations like data interoperability, scalability, and regulatory readiness. A novel contribution of this review is the conceptualization of an integrated DT hub that enables closed-loop pharmaceutical intelligence, offering real-time, end-to-end optimization across the drug lifecycle. The findings underscore the strategic importance of AI-powered Digital Twins in shaping the future of sustainable and patient-centric pharmaceutical systems.

**Keywords:** Digital Twin; Pharmaceutical Manufacturing; Pharmacy; Drug Lifecycle; Smart Supply Chain

## 1. Introduction

The pharmaceutical industry faces growing pressure to improve supply chain resilience, advance personalized care, and reduce environmental impact. Disruptions like the COVID-19 pandemic and rising chronic disease burdens have exposed vulnerabilities in pharmaceutical manufacturing and distribution, especially in low-resource regions [2]. Traditional systems often operate reactively, struggling to maintain quality and availability amid regulatory and market shifts [2]. Emerging technologies such as Digital Twins (DTs) and Artificial Intelligence (AI) offer a path forward by enabling intelligent, data-driven systems that improve visibility, efficiency, and adaptability across the pharmaceutical lifecycle. DTs—virtual representations of physical assets or systems—can be paired with AI to support simulation, optimization, and predictive decision-making in real-time [1, 4, 6].

DT systems in the pharmaceutical sector rely on a triad of integrated components. First, software platforms serve as the digital core, leveraging AI algorithms, advanced analytics, and cloud infrastructures to process real-time data at scale. This enables process simulation, monitoring, and early forecasting of inefficiencies [10, 17, 28]. Second, hardware components—IoT sensors, embedded systems, and monitoring devices—collect temperature, pressure, and chemical

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composition data to support quality control and regulatory compliance [1, 3, 4, 15, 22, 28]. Third, development platforms allow engineers and data scientists to create and test digital models tailored to specific manufacturing or logistics scenarios, enhancing agility and reducing implementation risk [7, 20, 23, 26]. Figure 1 illustrates the closed-loop interaction between IoT data collection, AI analytics, and digital twin systems for real-time optimization across pharmaceutical applications.

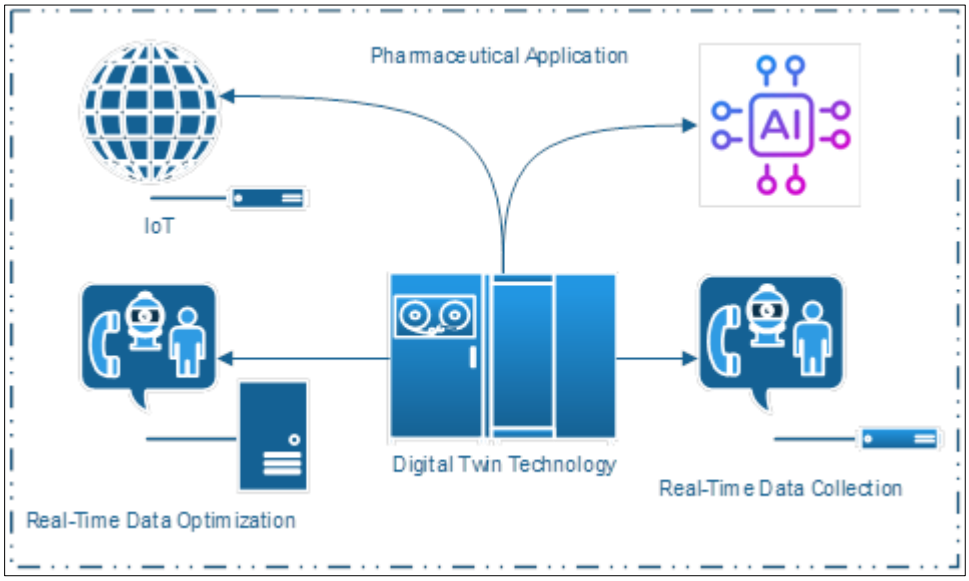


**Figure 1** Digital Twin Technology Integration for Pharmaceutical Applications

This literature review draws on findings from 29 peer-reviewed studies to explore how DTs and AI support various *pharmaceutical* domains. It defines enabling technologies in digital transformation, evaluates their role in advancing sustainability and resilience, and identifies research gaps and future opportunities for end-to-end pharmaceutical innovation.

## 2. Literature review

This review employed a targeted search strategy across databases, including Scopus, Web of Science, and Google Scholar, to identify peer-reviewed studies published between 2020 and 2024 on Digital Twin and AI applications in pharmaceutical contexts. The search terms targeted key domains such as pharmaceutical manufacturing, supply chain logistics, sustainability, and personalized medicine. Studies were selected based on relevance to pharmaceutical use cases, technological implementation, and contribution to end-to-end system integration. Excluded materials focused solely on non-pharma industries or lacked technical specificity. Data extracted included research objectives, methods, DT types, enabling technologies, and reported outcomes to support a comprehensive synthesis of current advancements.

### 2.1. Digital Twin Applications in Pharmaceutical Manufacturing

Digital Twin (DT) technology revolutionizes pharmaceutical manufacturing by enabling real-time monitoring, predictive analytics, and informed decision-making across production environments. Rather than serving discrete tasks, DT systems integrate data from various sources to enhance quality control, reduce operational costs, and minimize waste throughout manufacturing operations [4, 5, 24].

#### *2.1.1. Real-Time Process Monitoring*

DTs allow manufacturers to monitor every phase of the production cycle—from raw material acquisition to final product release. By integrating real-time sensor data with virtual models, DTs simulate operational environments and enable accurate, on-the-fly monitoring [7, 4]. For example, DTs monitor temperature, pressure, and chemical concentrations in biologics production, ensuring process consistency and compliance with regulatory standards [24]. Beyond monitoring, DTs also enable feedback control by adjusting process parameters dynamically in response to real-time sensor inputs. In advanced facilities, sensor-integrated DTs are coupled with AI algorithms to refine process control strategies, enhancing stability and output quality. Raudenbush et al. [16] and Ullagaddi [26] reported that such

integrations helped anticipate equipment malfunction, automate interventions, and maintain manufacturing continuity without manual oversight. This real-time responsiveness is essential for identifying deviations from expected process parameters and initiating corrective actions early. In GMP-compliant settings, researchers have shown that DTs enhance quality assurance and reduce unexpected downtimes by predicting performance anomalies [14, 16, 26].

#### *2.1.2. Resource Optimization and Waste Reduction*

A key advantage of DTs in manufacturing is their role in optimizing resource consumption. DTs simulate various production scenarios to identify the most efficient pathways—minimizing energy use, raw material waste, and processing time [22, 13]. In green pharmaceutical initiatives, DTs have supported energy-optimized workflows, reduced environmental impact while sustained productivity [17, 22]. In a study by Tegtmeier et al. [22], green manufacturing of herbal remedies was supported by DT-guided simulations that reduced excess energy usage and minimized solvent waste. Similarly, Silva et al. [18] demonstrated how DTs were applied in high-throughput chromatographic development to optimize buffer consumption and improve purification efficiency, underscoring their role in driving sustainable manufacturing practices. Blockchain-enabled DTs further contribute to transparency and traceability by securing data exchanges and providing an immutable audit trail across production stages [12]. This capability is critical in complex pharmaceutical systems requiring tight cross-functional coordination and strict regulatory compliance.

#### *2.1.3. Regulatory Compliance Enablement*

Regulatory oversight in pharmaceutical manufacturing demands accuracy, traceability, and transparency. DTs assist companies in complying with industry standards by generating real-time logs, simulating audit scenarios, and alerting teams to potential violations [10, 26]. They enable regulatory simulations to flag quality risks before they escalate, reducing the likelihood of recalls or non-compliance penalties [7]. AI-enabled DTs enhance digital compliance by automatically generating and maintaining audit-ready records. These systems help pharmaceutical companies meet evolving international guidelines, including FDA and EMA regulations on electronic records and process traceability. By supporting continuous documentation and tracking anomalies, DTs reduce the administrative burden of compliance while improving operational transparency [10, 26]. Moreover, these systems enhance reporting capabilities by capturing high-resolution data across production environments, making them valuable assets during inspections and quality audits [24, 16].

#### *2.1.4. Application Case: Adjuvant Manufacturing Optimization*

Phalak et al. [14] demonstrated a practical application of Digital Twins (DTs) in adjuvant production. Their study developed a DT to control particle size—a critical quality attribute—by dynamically adjusting real-time temperature and inlet flow rates. The model used Process Analytical Technology (PAT) combined with machine learning to improve responsiveness and optimize output quality. This study aligns with broader findings by Mariam et al. [10], who noted that generative AI models embedded in DTs can further reduce experimental iterations and accelerate decision-making in pharmaceutical production. Such models support intelligent automation and adaptive learning, making manufacturing more responsive to process variability and patient-specific product customization demands.

This DT was first validated under controlled laboratory conditions and then successfully deployed in a GMP environment. It reduced experimental costs, improved reproducibility, and enabled more robust control over key production variables. A related application by Zobel-Roos et al. [29] employed a DT-based framework to design and validate a continuous peptide polishing step using MATLAB simulations and the general rate model. Their implementation resulted in a 27.6% increase in yield, a 26.6% improvement in productivity, and a 20.2% reduction in eluent consumption—demonstrating the tangible benefits of DTs in sustainable, high-efficiency downstream processing. These cases illustrate how teams can scale DTs from prototypes to fully compliant industrial systems that enhance quality and sustainability in pharmaceutical manufacturing [25, 29].

### 2.2. Digital Twins for Supply Chain and Cold Chain Logistics

Pharmaceutical supply chains are susceptible to disruptions, especially in transporting and storing temperature-dependent products such as biologics and vaccines. Traditional cold chain systems often lack real-time visibility and predictive capabilities, making them vulnerable to breakdowns that compromise product quality and compliance. Digital Twins (DTs) address these gaps by providing virtual representations of supply chain networks continuously updated with real-time sensor data [28, 20].

*2.2.1. Real-Time Environmental Monitoring and Control*

DTs enable end-to-end environmental monitoring by integrating IoT sensors into logistics infrastructure. These systems track key variables such as temperature, humidity, vibration, and pressure, continuously feeding data into virtual models to ensure that environmental conditions remain within acceptable limits [28]. Wu et al. [28] demonstrated how DTs were applied in pharmaceutical cold chains to monitor refrigerated units during vaccine transport, immediately flagging deviations and allowing corrective interventions to prevent spoilage. Leeming et al. [8] also applied DTs in temperature-sensitive crystallization environments, showing their ability to manage supersaturation levels through continuous process feedback. These models help ensure product stability during long-haul distribution, especially for sensitive biological compounds.

*2.2.2. Predictive Disruption Management*

Beyond reactive monitoring, DTs support predictive disruption management by analyzing historical logistics data in combination with real-time feeds. These capabilities allow pharmaceutical distributors to anticipate cold storage equipment breakdowns or route delays caused by weather or traffic [20, 28]. For instance, Spyrou et al. [20] demonstrated how a virtual twin forecasted route obstructions during cannabis product shipments, which enabled the team to reroute deliveries in advance. Tetteh-Caesar et al. [23] highlighted how such predictive insights align with Lean 4.0 objectives by reducing downtime and supporting just-in-time delivery strategies. This approach improves product security and operational efficiency, mainly when distributing medicines across regions with variable infrastructure reliability.

*2.2.3. Efficiency Optimization and Sustainability*

DTs also enhance cold chain efficiency by allowing stakeholders to test and refine logistics strategies in virtual environments. Simulations can optimize warehouse configurations, packaging methods, delivery schedules, and fuel consumption before changes are implemented physically [20, 28]. These trials contribute to reducing carbon emissions, shipping costs, and product waste. Tegtmeier et al. [22] noted that energy optimization strategies informed by DTs have contributed to more sustainable pharmaceutical supply chains. In particular, packaging simulations using DTs allowed companies to identify biodegradable or thermally efficient materials that maintained product integrity while reducing environmental impact [16, 24]. In some cases, lifecycle carbon footprints of transportation and packaging combinations were modeled to guide environmentally responsible logistics choices [22]. Moreover, DT-driven logistics planning supports compliance with global sustainability frameworks and contributes to environmental, social, and governance (ESG) reporting efforts aligned with Pharma 4.0 goals [10, 12].

*2.2.4. Application Case: Cold Chain Optimization in Vaccine Distribution*

Wu et al. [28] reported a 15% reduction in biological product loss after implementing a real-time DT-driven monitoring system that tracked environmental variables. This system enabled proactive interventions during shipping and storage. Similarly, Spyrou et al. [20] described how DTs forecasted weather-related disruptions during vaccine distribution, allowing companies to reroute shipments in advance and prevent delivery delays. These applications reflect the strategic value of DTs in strengthening supply chain resilience. By pairing predictive analytics with real-time logistics oversight, DTs help pharmaceutical firms reduce risk, improve traceability, and ensure regulatory compliance in cold chain operations [10, 16].

### 2.3. AI-Augmented Digital Twins for Sustainability

Sustainability has become a central concern in pharmaceutical manufacturing, driven by regulatory mandates, corporate ESG goals, and global climate initiatives. AI-augmented Digital Twins (DTs) present a promising solution for improving resource efficiency, reducing environmental footprint, and enhancing predictive maintenance practices [10, 19, 22]. AI-enabled DTs can simulate, predict, and optimize complex manufacturing processes to meet sustainability benchmarks by integrating real-time data with machine learning algorithms.

*2.3.1. Predictive Maintenance for Energy Efficiency*

One significant sustainability benefit of AI-integrated DTs is predictive maintenance. Rather than relying on time-based maintenance schedules, AI-enabled DTs assess real-time sensor data to predict wear, failure, or inefficiencies in equipment [14, 10]. This approach allows pharmaceutical plants to address potential faults before they escalate—avoiding unplanned downtime and reducing energy waste from inefficient machines [24]. Tegtmeier et al. [22] illustrated how predictive analytics, supported by DT platforms, were used to reduce heating and cooling energy demands in herbal drug production. Similarly, Raudenbush et al. [16] emphasized how early intervention through DTs extended equipment lifespan, reducing replacement needs and supporting circular manufacturing models.

*2.3.2. Resource Optimization through Process Simulation*

When powered by AI, DTs allow manufacturers to model thousands of production scenarios, identifying the most efficient combination of inputs such as raw materials, solvents, energy, and time [17, 20]. This simulation capability supports lean manufacturing and reduces waste generation across multiple steps in the pharmaceutical value chain. Silva et al. [18] studied how DTs can optimize high-throughput chromatographic purification for monoclonal antibodies, reducing buffer volumes and improving operational throughput. Simulating adjustments without disrupting live production also allows companies to experiment with greener alternatives and fine-tune performance under new regulatory conditions [10].

*2.3.3. Sustainable Packaging and Lifecycle Impact Modeling*

Packaging represents another area where AI-driven DTs promote environmental sustainability. By simulating the behavior of different packaging materials across various environmental conditions, DTs help identify solutions that reduce material use while maintaining thermal and structural integrity [16, 24]. Fischer et al. [4] emphasized how thermal modeling within DT systems enabled pharmaceutical firms to select less resource-intensive packaging without compromising cold chain protection. Additionally, DT-based simulations supported product lifecycle assessments, including transportation loads and waste disposal impacts, facilitating better alignment with global sustainability metrics [22].

*2.3.4. Application Case: Energy and Water Reduction in Biologic Manufacturing*

In a biologics manufacturing facility, AI-powered DTs enabled a 15% decrease in energy use by adjusting mixing speeds, heating, and cooling operations based on predictive analytics [22]. The system learned from historical data patterns to refine equipment operation windows, optimizing energy use without compromising product output. Another study described by Mariam et al. [10] and Raudenbush et al. [16] focused on water conservation. By monitoring real-time water usage across facilities, the DT identified inefficiencies in cleaning cycles and enabled automated adjustments—ultimately leading to a 10% reduction in water consumption without compromising GMP compliance. These cases highlight how AI-integrated DTs go beyond process monitoring to create adaptive, environmentally responsible manufacturing systems. They reinforce the technology's role in achieving cost-efficiency and climate-conscious production goals.

### 2.4. Digital Twins for Personalized Medicine and Drug Discovery

Unlike traditional one-size-fits-all models, Digital Twins (DTs) enable virtual simulations of individual patients or drug interactions, allowing more accurate treatment planning and faster therapeutic breakthroughs [1, 3, 4].

*2.4.1. Patient-Specific Twins and Tailored Therapies*

DTs can create personalized patient avatars by modeling physiological, genetic, and environmental data. These models help simulate disease progression and predict individual responses to various treatment options [3, 1]. In chronic pain management, Bahrami et al. [3] utilized DTs to optimize transdermal fentanyl delivery by accounting for patient-specific skin properties and metabolic rates. Similarly, Abdollahi et al. [1] applied DTs in radiopharmaceutical therapy to model tumor response and optimize dosing strategies based on receptor expression and biodistribution patterns. Such personalization improves efficacy and minimizes adverse effects by eliminating the need for generic dosing protocols.

*2.4.2. AI-Powered Drug Discovery and Modeling*

In drug development, DTs enable in silico testing of pharmaceutical compounds, significantly reducing the time and cost associated with early-stage trials. By integrating omics data and biological pathway models, researchers can simulate drug-target interactions under various physiological conditions [10, 4]. Mariam et al. [10] and Fischer et al. [4] showed how researchers use AI-powered DTs to evaluate pharmacodynamics and toxicity at the cellular level. These simulations inform compound selection, dose prediction, and formulation design, ultimately accelerating preclinical pipelines.

*2.4.3. Improving Outcomes Through Adaptive Treatment Models*

DTs also support adaptive therapy by updating models based on patient monitoring data. In oncology, for example, DTs simulate tumor growth trajectories and treatment responses in real-time, allowing clinicians to modify regimens as new imaging or genomic data becomes available [1, 9]. These capabilities extend to managing chronic illnesses, where DTs model adherence behaviors, metabolic shifts, and comorbid risks. Meijer et al. [11] emphasized the need for further research on integrating diverse data sources to improve real-time decision support in clinical settings.

*2.4.4. Application Case: Generative Digital Twins in Biologic Modeling*

Recent innovations involve generative AI models that simulate cellular responses to drug candidates. Bordukova et al. [10] reported using digital twins trained on multi-omics datasets to predict gene-level perturbations and treatment efficacy in silico. This approach has been particularly valuable in developing personalized combination therapies for complex diseases such as cancer and autoimmune disorders. By predicting treatment response before clinical administration, DTs help reduce trial-and-error in therapy planning, lower development costs, and improve patient safety. Together, these developments underscore the transformative role of DTs in creating a more adaptive, personalized, and efficient pharmaceutical landscape.

Table 1 illustrates the breadth of DT use cases—from manufacturing process optimization and cold chain logistics to personalized medicine and AI-driven drug discovery. It also emphasizes enabling technologies such as machine learning, virtual reality, and omics-based modeling to achieve measurable improvements in efficiency, quality, sustainability, and patient outcomes.

**Table 1** Digital Twin Frameworks Across Pharma Domains

| Author(s) | Type of DT developed | Methodological framework | Application area | Results |
|---|---|---|---|---|
| Phalak et al. [14] | Process DT for adjuvant particle size control | PAT + Machine Learning | Pharmaceutical manufacturing (GMP) | Improved quality control; reduced trial costs; real-time control |
| Silva et al. [18] | High-throughput purification DT | Chromatographic simulation | Biologic manufacturing | Reduced buffer use; optimized purification cycles |
| Leeming et al. [8] | Crystallization process DT | Supersaturation monitoring | Temperature-sensitive formulation | Stabilized crystallization outcomes; predictive control |
| Fischer et al. [4] | Biological simulation DT | AI + Omics data integration | Personalized medicine | Simulated drug responses; enabled tailored treatment discovery |
| Spyrou et al. [20] | Logistics DT with VR interface | Virtual Reality + Semantic modeling | Pharmaceutical logistics (cannabis) | Anticipated disruptions; improved routing |
| Mariam et al. [10] | Drug discovery DT | Generative AI simulation | In silico drug development | Preclinical evaluation; reduced R&D cycle time |
| Tegtmeier et al. [22] | Green manufacturing DT | Energy modeling & optimization | Sustainable pharma production | 15% energy savings; improved ESG alignment |
| Wu et al. [28] | Cold chain logistics DT | IoT sensor integration | Vaccine distribution | 15% reduction in product loss; enhanced traceability |
| Bahrami et al. [3] | Patient-specific DT | Skin-permeability + pharmacokinetic modeling | Chronic pain therapy | Personalized fentanyl dosing; improved safety |
| Abdollahi et al. [1] | Radiopharmaceutical DT | Receptor expression modeling | Cancer treatment planning | Customized dosing; improved therapeutic precision |

## 3. Discussion: Integration, Challenges, and Future Directions

This review highlights how Digital Twins (DTs) shape key pharmaceutical domains, including personalized medicine, predictive manufacturing, and supply chain optimization. To move beyond siloed applications, researchers and industry leaders must integrate these systems into a unified, intelligent ecosystem that enables closed-loop data exchange and proactive decision-making across the drug lifecycle. This study focuses on publicly available peer-reviewed literature, which excludes proprietary or unpublished advancements. Much existing evidence relies on conceptual models or pilot studies with limited long-term data. To fully realize the potential of DTs, future work must prioritize empirical validation and foster stronger collaboration across disciplines and sectors [5, 21].

### 3.1. Cross-Domain Integration and Systems Convergence

Our synthesis reveals fragmentation in current DT implementations: manufacturing-focused DTs optimize production processes, while clinical DTs simulate patient-specific responses. This review advances the literature by proposing a more integrated architecture. This end-to-end digital twin framework connects early-stage drug design, manufacturing, supply chain logistics, and personalized treatment. The dynamic interaction between these layers would allow manufacturing specifications, such as dosage form properties or excipient sensitivities, to inform clinical dosing models that adapt based on patient-level feedback. Such a system would require interoperable DTs capable of translating physical process parameters into personalized digital care models. Although no current study fully achieves this integration, early steps toward this vision are evident in DTs that model downstream crystallization behaviors or simulate patient pharmacodynamics. The convergence of these capabilities could create a real-time loop where manufacturing and treatment co-evolve, ultimately shortening drug development timelines and improving therapeutic outcomes.

### 3.2. Adoption Barriers and Digital Readiness

Despite compelling use cases, scaling DTs across pharmaceutical networks presents significant challenges. Infrastructure deficits in low- and middle-income regions remain a barrier to implementation, with many firms lacking the IoT connectivity, cloud infrastructure, or digital literacy required to deploy complex twin ecosystems [2, 23]. Data silos persist even in digitally mature companies, often due to a lack of semantic alignment between operational, regulatory, and clinical datasets [12, 27]. Importantly, this review highlights a critical but underexplored barrier: organizational and human limitations. The successful deployment of DTs depends not just on hardware and software but also on workforce readiness, cross-disciplinary collaboration, and cultural acceptance of automation. These human-centered gaps are seldom addressed in technical studies but remain pivotal to real-world scalability. To ensure successful adoption, future implementation efforts must include comprehensive change management strategies, workforce training, and co-design approaches.

### 3.3. Regulatory, Ethical, and Governance Concerns

Digital Twins in healthcare and pharmaceutical supply chains generate vast amounts of sensitive data, raising questions about privacy, accountability, and validation. Current frameworks for Good Manufacturing Practice (GMP), GxP, and FDA guidelines often fail to align with the autonomous decision-making systems that DTs incorporate. For instance, DTs capable of autonomously adjusting dosages or altering logistics flows in real-time challenge conventional audibility and compliance models [11, 13]. This review uniquely underscores the risk of regulatory lag. While technological innovations in DTs outpace existing governance systems, companies must navigate ambiguity in ethical norms, particularly in patient-facing applications. As DTs become more autonomous and predictive, regulatory science must evolve to validate static models and dynamic learning systems that continuously adapt to new data. Moreover, ethical frameworks must address consent, explainability, and data ownership in increasingly complex AI-augmented environments.

### 3.4. Future Research and Innovation Pathways

Looking ahead, several innovation pathways offer promise. Future work should prioritize the design of hybrid Digital Twin (DT) frameworks that unify clinical, manufacturing, and logistical data streams into a single interoperable model. Such frameworks must support multi-scale modeling, ranging from molecular-level simulations in drug design to macro-level logistics coordination. Another promising avenue is the standardization of DT ontologies, which would support plug-and-play modularity across platforms and enable faster technology transfer between institutions and regulatory bodies. Research is also needed in generative DT models that simulate virtual patient populations, allowing for accelerated in silico trials that reduce dependence on costly physical experimentation. Furthermore, sustainability metrics—such as carbon emissions, material efficiency, and lifecycle impact—should be embedded directly into DT platforms to align pharmaceutical innovation with environmental goals.

This review contributes a novel perspective by framing DTs not merely as tools for optimization but as systemic enablers of closed-loop pharmaceutical intelligence. By interconnecting physical production, digital simulation, and clinical application, future DT systems could drive the next wave of innovation in global health: real-time, personalized, sustainable, and scalable. Figure 2 presents a conceptual diagram illustrating how a centralized Digital Twin Hub integrates Artificial Intelligence (AI) and the Internet of Things (IoT) across drug discovery, manufacturing, and supply chain domains to support personalized medicine, optimized resource use, and regulatory compliance.

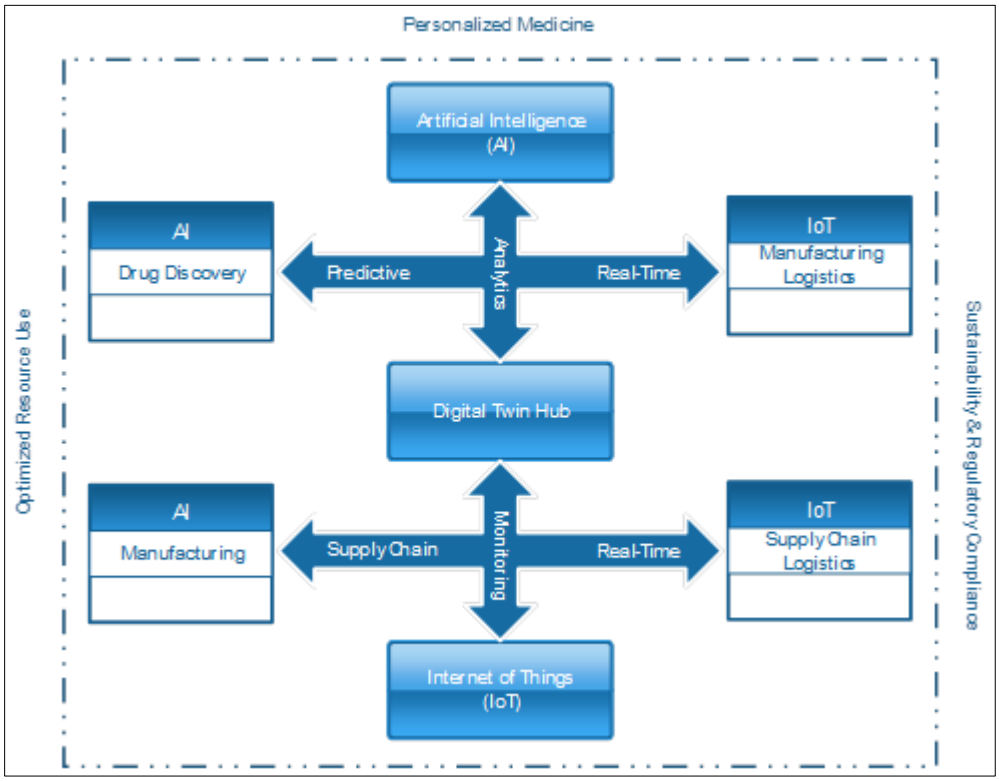


**Figure 2** Conceptual Diagram of Digital Twin Hub Across Pharmaceutical Lifecycle

Table 2 illustrates a novel perspective by mapping the converging roles of Digital Twins across different pharmaceutical domains. It highlights how various DT systems—manufacturing, logistics, sustainability, clinical care, and R&D—can interact through shared data flows to support an integrated, end-to-end pharmaceutical intelligence framework.

**Table 2** Converging Roles of Digital Twins Across the Pharmaceutical Lifecycle

| DT Domain | Primary Objective | Key Technologies | Data Flow Interactions | Potential for Integration |
|---|---|---|---|---|
| Manufacturing | Process optimization and quality control | IoT, AI, PAT, cloud analytics | Feeds real-time production data to supply and clinical twins | High – can inform formulation parameters for clinical dosing |
| Supply Chain & Logistics | Real-time tracking and environmental control | IoT, Blockchain, DT-enabled route simulation | Ingests production specs; shares status with clinical DTs | Medium – critical for traceability and compliance |
| Sustainability Modeling | Reduce energy and material waste | AI/ML optimization, lifecycle impact models | Draws from process DTs; reports to ESG dashboards | High – supports green manufacturing alignment |
| Personalized Medicine | Simulate individual response to therapy | AI, multi-omics data, patient DTs | Uses drug formulation data and adjusts via feedback loops | Very High – central to closed-loop care delivery |

| | | | | |
|---|---|---|---|---|
| Drug Discovery & R&D | Accelerate compound testing and simulation | Generative AI, virtual trials, omics DTs | Produces optimized profiles fed into clinical DTs | Medium – needs integration with patient-specific models |

## 4. Conclusion

This review highlights the transformative potential of Digital Twin (DT) and Artificial Intelligence (AI) technologies across the pharmaceutical lifecycle. DTs enable more intelligent manufacturing, resilient supply chains, sustainable operations, and individualized therapies—positioning them as foundational tools in healthcare's digital evolution. While current applications remain largely siloed, the future lies in developing unified, interoperable DT systems that support closed-loop optimization from drug development to delivery. Addressing data interoperability, infrastructure gaps, and regulatory readiness will be critical to realizing this vision. By framing DTs as systemic enablers rather than isolated tools, this review offers a strategic perspective on their role in building intelligent, scalable, and sustainable pharmaceutical systems.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors declare that they have no conflicts of interest to disclose.

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