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DIGITAL TWINS IN ANTIMICROBIAL STEWARDSHIP: A MULTI-SCALE REVIEW OF APPLICATIONS, ENABLING TECHNOLOGIES AND IMPLEMENTATION BARRIERS

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ABSTRACT

Objective: To synthesise contemporary and ongoing evidence on digital twin (DT) applications in antimicrobial stewardship (AMS) across the patient, ward, and health-system levels, and to differentiate digital twins conceptually from traditional artificial-intelligence (AI)-based stewardship decision support.

Methods: Narrative review of peer-reviewed and important and significant preprint literature issued up to July 2026, identified through PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore, ScienceDirect, and medRxiv. Findings were organised thematically into patient-, ward-, and system-level applications, permitting technologies, and implementation obstacles.

Results: At the patient level, digital twins built on population pharmacokinetic-pharmacodynamic models and Bayesian forecasting support individualised antibiotic dosing, real-time exposure observation, and previous de-escalation. At the ward and hospital level, agent-based and graph-structured digital twins simulate nosocomial pathogen transmission, permitting infection-prevention interventions to be tested virtually before physical implementation. At the system level, emerging hospital- and population-scale digital twins integrate monitoring data to predict opposition trends and optimise stewardship policy. Persistent hurdles contain data quality and compatibility, model validation and clinician trust, computational cost, regulatory uncertainty, cybersecurity, and the risk of widening resource-based inequity.

Conclusion: Digital twins constitute a conceptually distinct and complementary advance over existing decision-support tools, with the potential to unify diagnostic, therapeutic, and policy dimensions of stewardship within a single adaptive framework. Rigorous prospective validation, governance structures, and equitable deployment strategies remain prerequisites for their responsible translation into routine clinical practice.

Keywords: Digital twin; antimicrobial stewardship; antimicrobial resistance; precision dosing; artificial intelligence in medicine; model-informed precision dosing; agent-based simulation; clinical decision support; vancomycin

Abbreviations: AMR, antimicrobial opposition; ASP, antimicrobial stewardship programme; DT, digital twin; MIPD, model-informed precision dosing; PK/PD, pharmacokinetic-pharmacodynamic; AUC, area under the curve; MIC, minimum inhibitory concentration; HER, electronic condition record; IoT, Internet of Things; ICU, intensive care unit; CDC, Centers for

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Disease Control and Prevention; GRAM, Global Research on Antimicrobial Resistance; GBD, Global Burden of Disease; AI, artificial intelligence; ML, machine learning; IV, intravenous; SaMD, Software as a Medical Device; MRSA, methicillin-resistant Staphylococcus aureus; AWaRe, Access, Watch, Reserve; GLASS, Global Antimicrobial Resistance and Use Surveillance System.

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INTRODUCTION

Antimicrobial opposition (AMR) has shifted from a background concern of infectious disease specialists to one of the defining public condition threats of the twenty-first century. The 2019 GRAM analysis calculated bacterial AMR was associated with 4.95 million deaths and directly attributable to 1.27 million that year, with the heaviest strain in reduced respiratory, bloodstream, and intra-abdominal infections, and in sub-Saharan Africa and South Asia [1]. An extension to 1990-2021, with predictions to 2050, projects attributable deaths rising from 1.14 to 1.91 million per year and associated deaths from 4.71 to 8.22 million; though this trajectory is not immutable, as enhanced infection care and a strengthened pipeline could avert tens of millions of deaths [2].Antimicrobial stewardship programmes (ASPs) — ensuring antimicrobials are used only when they confer clear benefit — are among the most evidence-supported interventions for slowing this trajectory. Frameworks such as the CDC Core Elements organise ASP activity around leadership, accountability, pharmacy expertise, priority interventions, tracking, reporting, and education [3,4]. Digital interventions — decision support, audit-and-feedback dashboards, prescribing restrictions — reduce antimicrobial use and improve appropriateness across multiple reviews, though effects on mortality and length of stay remain variable [5,6,7,8].

Conventional digital ASP tools share a limitation: most operate as static decision points, uninformed by how physiology, pathogen behaviour, or ward transmission will evolve. Digital twin (DT) technology, first formalised in aerospace and manufacturing as a persistent virtual counterpart continuously synchronised through sensor data [9,10],provides a dissimilar proposal: a living simulation that forecasts forward and tests interventions in silico before physical application. Health digital twins have been investigated for precision cardiology [11,12], oncology, and population condition [13], and a growing, still-nascent body of work now extends the idea to antimicrobial stewardship; dosing, sepsis forecasting, transmission simulation, opposition forecasting [14,15,16].

This review addresses three queries: What is digital twin technology‘s basis, and how does it differ from AI instruments already used in stewardship? What applications have been reported at the patient, ward, and system levels, and how mature is the evidence? What obstacles must be overcome before routine adoption? We synthesise the responses into a multi-scale framework for clinicians, pharmacists, infection-control practitioners, and condition informaticians.

REVIEW METHODOLOGY

This is a narrative rather than systematic review; no meta-analytic pooling or PROSPERO registration was undertaken, though the search followed a structured, reproducible process (Figure 1). Literature published up to 31 July 2026 was identified through PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore, ScienceDirect, and medRxiv, combining 'digital twin', 'antimicrobial stewardship/resistance', 'sepsis prediction', 'PK/PD modelling', 'Bayesian forecasting', 'precision dosing', and 'agent-based simulation' with adjacent engineering terms. Of 1,842 records identified, 316 duplicates were removed, 1,526 screened, 1,341 excluded, 185 full texts assessed, and 96 (peer-reviewed articles and credentialed preprints) retained for synthesis. Thematic extraction organised findings into patient-, ward-, and system-level applications, enabling technologies, and barriers, structuring Sections 5-8.

Fig. 1: Literature search and narrative synthesis workflow used for this review.

Source: Authors 'own collection, established on the process described in Section 2.

Limitations of this review methodology are specified in complete and entire in Section 11.

3. CONCEPT AND EVOLUTION OF DIGITAL TWIN TECHNOLOGY

3.1 Origins and Definition

The conceptual ancestor of the digital twin signs to NASA's Apollo programme in the 1960s, where engineers maintained a physical mirror vehicle on the ground to simulate and troubleshoot in-flight conditions [10]. The term was coined in 2010 by John Vickers of NASA to describe a triad: a physical entity, a virtual representation, and a bidirectional data connection keeping the two synchronised [10].Over the subsequent decade the idea matured within production and aerospace under Industry 4.0, where digital twins of jet engines, factories, and system enabled predictive upkeep long before entering clinical lexicon [17].

In medical care, a digital twin is now understood as a dynamic virtual representation of a patient, organ, care unit, or condition system, continuously updated with real-time data to simulate, monitor, and predict its physical equivalent [9,18,19,20]. This distinguishes it from a standard model: static models generate a single outcome from corrected input, whereas a digital twin persists across time, ingesting new data and updating its state consequently [9,18]. Some authors separate 'digital human twins'; thorough anatomical, physiological, and occasionally cognitive representations [9]; from organizational or population-scale

twins used operationally and epidemiologically [13].

3.2 Core Architecture

Functionally, a digital twin has three interacting components (Figure 2). The physical entity is the real-world system; patient, ward, or condition system; characterised by vitals, laboratory and microbiology outcomes, genomic/imaging data, and increasingly IoT streams. The virtual model usually combines mechanistic sub-models (for example, compartmental PK/PD equations) with machine-learning components capturing patterns mechanistic equations exclusively can not resolve [18,17].The data connection links the two bidirectionally: data update the virtual model, and outputs; predictions, risk scores, recommendations; flow back to notify action, closing a cyber-physical loop [17].

Fig. 2: Closed-loop architecture of a digital twin applied to antimicrobial stewardship.

Source: Authors 'own synthesis of the architecture described in [17,18,19].

This closed-loop attribute most sharply differentiates digital twins from previous decision support. A traditional dosing calculator or warning rule is asked once and returns a single recommendation; a digital twin is re-queried continuously as new measurements come, refining its approximation of the patient's, ward's, or system's trajectory at each step [9,18,21].

3.3 From Industry to the Bedside: A Timeline

The migration from aerospace to antimicrobial stewardship spans about six decades, but health- and stewardship-specific applications are new and fresh and still consolidating (Figure 3). Health digital twins for precision cardiology and population health appeared in the initial 2020s [11,12,13], establishing precedents; data fusion across omics, imaging, and clinical variables; Bayesian/mechanistic hybrid modelling; cyber-physical feedback; that stewardship applications have since modified. Reports integrating digital twin architecture with dosing, sepsis forecasting, or hospital-scale AMR simulation have appeared mainly since 2023, with hospital- and population-scale platforms first described in 2025-2026 [15,16].

Fig. 3: Timeline of the digital twin idea from aerospace origins to antimicrobial stewardship applications.

Source: Authors 'own collection, drawn from the chronology in Sections 1 and 3.

THE ANTIMICROBIAL RESISTANCE CRISIS AND THE justification FOR DIGITAL STEWARDSHIP

The scale of the AMR strain summarised in Section 1 offers the epidemiological reasoning for investment in new stewardship instruments (Figure 4). Three features are especially relevant. The strain is concentrated in a small number of syndromes and germs; reduced respiratory, bloodstream, and intra-abdominal infections account for most AMR-associated deaths, and five leading germs for more than half [1]; so digital twin efforts can plausibly achieve broad impact by concentrating at first on a limited set of high-burden goals. It is rising fastest where stewardship system is weakest: adults over 70 have seen the biggest increases, and most projected future strain drops on low- and middle-income countries with restricted laboratory and informatics capability [2]. And a significant and purposeful part is plausibly adaptable through better-timed, better-dosed, better-targeted application instead than new drug discovery solely; forecasting models suggest enhanced infection care could avert tens of millions of deaths even without a strengthened pipeline [2].

Fig. 4: Global mortality strain of bacterial antimicrobial opposition, noted (2019, 2021) and forecast (2050).

Source: Data derived from the GRAM 2019 and 2021 analyses [1,2].

Conventional ASPs address changeable application through ordered and methodical but largely retrospective processes: audit and feedback, formulary limitation, guideline distribution, education [3,4]. Reviews of digital ASP interventions verify computerised decision support and audit-and-feedback dashboards meaningfully lower consumption and improve appropriateness [5,6], though effects on length of stay, mortality, and cost are erratic, and sociotechnical aspects; clinician trust, workflow suitable, approval; continue underexplored relative to technical performance [5]. Digital instructive and informative interventions show steady and regular advantage for stewardship knowledge and short-term behaviour change but function upstream of, alternatively than instead of, real-time decision-making [7].

A complementary and increasingly central metric is the WHO‘s AWaRe (Access, Watch, Reserve) classification, which categorises antibiotics by resistance-selection potential and is now the main worldwide signal for benchmarking stewardship activity [26]. Because it assigns a stewardship-relevant label to every antimicrobial, AWaRe is a natural target variable for a system-level digital twin: one

that forecasts prescribing by AWaRe category, alternatively than consumption solely, could simulate the downstream opposition effects of shifting prescribing toward Access-group agents before a policy is executed.

Digital twins address a particular gap: the lack of a persistent, forward-looking model that can be interrogated continuously instead than at a single decision point, and that supports in-silico testing of alternative interventions before real-world application. The remainder of this review analyzes the evidence across three levels of application.

DIGITAL TWIN APPLICATIONS ACROSS THE ANTIMICROBIAL STEWARDSHIP CONTINUUM

Digital twin applications relevant to antimicrobial stewardship can be organised into three interacting scales: the individual patient, the ward or hospital, and the condition system or population (Figure 5). Although reported individually in the literature to date, these scales are conceptually designed to swap data and models,so that, for instance, patient-level pharmacokinetic estimates can notify ward-level transmission models, and ward-level outbreak simulations can advise system-level opposition forecasting.

Fig. 5: Multi-scale digital twin framework spanning patient, ward, and system levels of antimicrobial stewardship.

Source: Authors 'own synthesis of the patient-, ward-, and system-level literature examined in Section 5.

5.1 Patient-Level Digital Twins: Precision Pharmacokinetic-Pharmacodynamic Dosing

The most mature digital-twin-like application in antimicrobial stewardship are model-informed precision dosing (MIPD), integrating a population pharmacokinetic model with Bayesian forecasting to generate an individualised, continuously updated exposure approximation. Vancomycin dosing illustrates this well: accord direction now recommends AUC-guideddosing, targeting a 24-hour AUC/MIC ratio of approximately 400-600 (AUC24 ≈400-600 mg·h/L at MIC 1 mg/L), in preference to trough-only observing [22]. This necessitates a model that forecasts exposure from scant sampling and revises as new data come; the closed-loop behaviour defining a digital twin. Systematic assessments, comprising one restricted to continuous-infusion dosing, have identified the Goti and Okada population models as clinically appropriate and fitting for Bayesian forecasting [21,23,24], and simulations comparing equation-based with Bayesian-guided dosing

show the latter achieves consistent and stable AUC prediction previously, incorporating from a single first-interval trough sample [21]. HER-integrated Bayesian software has translated this into clinical instruments, with AUC-guided MIPD cohorts showing better and refined results versus trough-only dosing [22], while smartphone- and web-based applications extend model entry beyond expert centres [25,26].

In the authors 'view, these platforms satisfy the structural definition of a digital twin: a persistent, patient-specific model is linked bidirectionally to the patient through concentration sampling and used to simulate dosing options before administration. This is an interpretive position alternatively than settled agreement; most pharmacometricians describe Bayesian MIPD simply as Bayesian forecasting; and readers should treat it consequently. Extending this logic to other narrow-therapeutic-index antimicrobials (aminoglycosides, extended-infusion beta-lactams, antifungals) is a natural, already-underway expansion [14], recorded for paediatric infectious disease stewardship, where age-dependent physiology makes fixed-dose regimens prone to under- or over-exposure;the identical review extends the logic to therapeutic drug observation, IV-to-oral switching, and other physiologically variable groups; older adults and critically sick patients; disproportionately represented in the AMR mortality strain of Section 4 [2,14]. Table 1 summarises representative evidence.

Table 1: Representative evidence for patient-level digital twin applications in antimicrobial stewardship.

Domain	Digital twin function	Representative evidence	Stewardship advantage
Vancomycin AUC-guided dosing	Population PK model updated by Bayesian forecasting from 1-2 concentration samples to predict individual AUC/MIC exposure	Goti and Okada population models confirmed for Bayesian forecasting [21,23,24]; app-based MIPD implementations [25,26]	Fewer sub-therapeutic or toxic exposures; quicker attainment of target AUC24 400-600 mg·h/L
Outcome-linked MIPD	Electronic condition record-integrated commercially available Bayesian dosing software generating patient-specific dosing regimens	AUC-guided MIPD cohort associated with enhanced clinical results versus trough-only dosing [22]	Reduced nephrotoxicity; prior regimen optimisation
Sepsis trajectory forecasting	Fusion of vitals, laboratory trends, and history into an ensemble learning twin that continuously re-estimates deterioration risk	Digital twin plus dynamic ensemble learning framework for ICU sepsis prediction [15]; AI-augmented sepsis care evaluations [28,29]	Earlier recognition supports timely, directed (instead than empirical broad-spectrum) therapy

Domain	Digital twin function	Representative evidence	Stewardship advantage
Paediatric precision AMS	Age-adjusted PK/PD twins integrating host-response biomarkers to direct dose, span, and IV-to-oral switch	Narrative review of digital twins across paediatric infectious disease stewardship [14]	Individualised dosing despite ontogenetic variability; shorter redundant and superfluous exposure

5.2 Diagnostic and Host-Response Digital Twins: Sepsis and Early Deterioration

A second cluster objectives diagnosis and deterioration forecasting: prior identification of developing sepsis reduces reliance on empirical broad-spectrum therapy by permitting more aimed, better-timed treatment. Machine-learning models trained on HER data can predict sepsis onset ahead of clinical recognition, though a structured review highlights limited comparability and reproducibility across studies [28,29]. At least one framework has combined digital twin architecture with dynamic ensemble learning for ICU sepsis prediction, fusing physiological data, history, and laboratory trends into a continuously updated risk model with enhanced and upgraded accuracy across prediction windows relative to static ensembles [15];broader AI-in-sepsis evaluations treat digital twins as a natural extension, emulating progression and treatment response alternatively than a single score [28]. Clinically, the value lies in offering continuously updated setting for antimicrobial decisions; differentiating sepsis from other deterioration, informing empirical coverage, and, matched with the twins of Section 5.1, supporting previous de-escalation [14,28].

5.3 Ward- and Hospital-Level Digital Twins: Nosocomial Transmission and Infection Prevention

Stewardship is inseparable from infection avoidance, since nosocomial transmission both drives and is shaped by antimicrobial application. Agent-based ward simulation has a substantial pre-digital-twin history: initial ICU models calculated pathogen reproduction numbers from nurse-patient interactions and hand-hygiene adherence [30], and later frameworks modelled transmission of MRSA [31], Clostridioides difficile [32,33], and bloodborne germs utilizingtrue admission and contact data [34]. CTCmodeler reconstructs transmission routes from hospital-specific admission, swab, and contact-network data to generate ward-level incidence estimates for assessing infection-control approaches before implementation [35].

These models are the systematic precursor to explicitly labelled hospital digital twins. A framework for hospital-scale AMR forecasting incorporates mechanistic transmission simulation with temporal graph-

based prediction and limited intervention optimisation, benchmarked across empirical regimes and data-shift conditions so the methodology‘s limits can be characterised alternatively than presumed [16]. This is, as yet, an unrefereed preprint; the main present origin for hospital- and system-level digital twin assertions in stewardship, treated as initial and preparatory throughout. Ward-level twins offer two abilities: testinginterventions (hygiene, disinfection, screening, limitation) virtually before physical deployment [16,31,32,33], and, linked to patient-level twins, informing bedside risk stratification [16].

5.4 System- and Population-Level Digital Twins: Resistance Forecasting and Policy Simulation

At the broadest scale, digital twins are starting to predict opposition trends and support policy across a hospital system or region, depending on monitoring system; notably WHO‘s GLASS, aggregating standardised opposition and consumption data across countries [36], and the GRAM collaboration underpinning present and existing strain estimates [1,2]; to calibrate and confirm system-scale twins. The hospital AMR platform above [16] exemplifies this, framing intervention option as restricted optimisation (screening, separation, limitation under staffing and bed-capacity limits) instead than unconstrained simulation. Population-health twin assessments assert that extending applications from individuals to regionsare an essential following step, requiring real-time cross-institutional data sharing [13]; for stewardship, such twins could let a condition authority simulate the results of local formulary or constraint policies before committing resources; extending, at system scale, the identical in-silico logic patient-level MIPD already applies to dosing.

5.5 Special Populations

Section 5.1 already introduced the strongest case for digital twins in physiologically variable populations: age-dependent physiology in children, and shifting renal function or volumes of distribution in older or critically sick adults, make fixed-dose regimens prone to under- or over-exposure, and these groups are disproportionately represented in the AMR mortality strain of Section 4 [2,14].

6. FACILITATING TECHNOLOGIES AND DATA SYSTEM

The practicality of digital twin-based stewardship rests on a technology stack matured over the past decade. EHRs supply the longitudinal data anchoring most patient-level twins; without ordered and methodical, interoperable data, the bidirectional connection at the core of the architecture (Figure 2) can not be sustained [18,37]. Point-of-care and genomic diagnostics

provide the microbiological ground truth for calibrating and re-validating sub-models, keeping transmission twins aligned with the circulating opposition profile [16,35]. IoT sensors and continuous observation supply the near-continuous data diagnostic twins for sepsis forecasting require [15,17,28]. Cloud computing and scalable pipelines run Bayesian forecasting, agent-based simulation, and ensemble models at scale, allowing the revision cycles that keep a twin synchronised with a changing entity [16,17]. AI/ML; Bayesian procedures, ensemble learning, temporal graph-based models; fuse varied streams into forward-looking estimates, differentiating a digital twin from a basic dashboard [15,16]; cyber-physical, closed-loop architectures, borrowed from industrial practice, formalise how these assemble into the synchronise-simulate-act cycle of Figure 2 [17].

7. COMPARATIVE ANALYSIS: DIGITAL TWINS VERSUS CONVENTIONAL AI-BASED STEWARDSHIP TOOLS

It is significant to situate digital twins relative to the AI-based decision support already used in stewardship, since the two are occasionally conflated. Conventional instruments; antibiogram-informed warnings, classifiers, audit-and-feedback dashboards; have a fairly mature evidence foundation, with assessments reporting uniform and unchanging decreases in consumption and enhanced appropriateness [5,6,7], but are normally asked at a single decision point alternatively than maintaining a persistent, forward-simulating model.Digital twins differ along the dimensions in Table 2: they persist and revise continuously; they more frequently integrate diagnosis, dosing, and policy testing within one framework; and their central contribution is in-silico simulation of counterfactual interventions before implementation, largely absent from traditional stewardship AI. This carries a greater validation strain; a twin must continue precise and correct over a complete and entire episode, outbreak, or policy horizon [16,37]; so the evidence foundation is best characterised as emerging: proof-of-concept and initial Bayesian MIPD studies plus a small, growing number of hospital-scale platforms, against the more established foundation for traditional digital ASP interventions [5,6,15,16].

Table 2: Comparative attributes of traditional AI-based clinical decision support and digital twin-based techniques to antimicrobial stewardship.

Parameter	AI-based clinical decision support	Digital twin-based techniques
Model & temporal behaviour	Single classifier/rule set, static prediction refreshed exclusively when re-queried	Persistent, continuously updated duplicate; predictions and re-forecasts as data come, closing a feedback loop
Scope	Usually one task (for example, flag an interaction, suggest a regimen)	Can integrate diagnosis, dosing, de-escalation, and policy testing within one framework
Simulation capability	Limited; seldom models counterfactual situations	Central feature; in-silico testing of alternative doses or policies before real-world application
Evidence foundation & validation strain	Reasonably mature [5,6,17]; balanced validation strain	Emerging [15,16]; greater strain; both sub-model and data-fusion pipeline need validation over time

8. PROBLEMS AND OBSTACLES TO IMPLEMENTATION

8.1 Data Quality, Interoperability, and Model Validity

Digital twins are exclusively as consistent and stable as the data connection sustaining them. Meta-reviews of condition digital twin implementation recognize limited admittance to high-quality, interoperable data as the most-cited obstacle, alongside the lack of standardised approaches and randomised evidence for clinical validity [37,38]. In stewardship this is compounded by varied microbiology reporting, the lag between specimen collection and susceptibility outcomes, and fragmented clinical, pharmacy, and laboratory data systems [16,37].

8.2 Ethical, Legal, and Governance Issues

Because digital twins rely on sustained entry to sensitive longitudinal data, they raise privacy and security concerns beyond standard, single-query decision support [37,39,40]. A new and fresh thematic analysis of moral, legal, and social problems in medical care digital twins spans technology, data, workflow, and management domains, recommending risk-stratified data standards aligned with device-risk classifications, privacy-preserving architectures, and explicit permission [39]. Regulatory pathways persist unsettled, and frameworks for simpler software-as-a-medical-device products may not capture a continuously updating, closed-loop model [37,38,39]. Two documents address this directly: the IMDRF‘s risk-categorisation framework for Software as a Medical Device [41], and the US FDA’s direction on pre-

established change control plans for AI-enabled device software, permitting adaptive algorithms to revise within a pre-agreed envelope alternatively than requiring re-approval each time [42].

8.3 Computational Cost, Clinical Trust, and Workflow Integration

Sustaining a continuously updated model at any scale are computationally demanding, and several hospitals; especially smaller, resource-limited organizations; lack the system and proficiency required [37,38]. Stakeholder interviews applying implementation-science frameworks recognize data-related, financial, operational, organisational, personnel, regulatory, and technological hurdles converging across clinician, administrator, and technical groups, with trust and workflow suitable recurring as concerns distinct from technical performance [43]. Without prospectively confirmed, clinician-observable improvement, digital twin instruments risk the identical underuse and alert fatigue that limited previously decision-support systems [5,43].

8.4 Equity, Feasibility, and an Indian and South Asian Perspective

The identical resource necessities risk concentrating advantages in well-resourced systems, even though AMR strain is supreme and paramount where system is weakest [2,38]. Absent intentional design for lower-resource deployment; lightweight, smartphone- or basic-server-based MIPD alternatively than total and whole hospital-scale platforms [25,26]; digital twin stewardship risks widening the worldwide AMR imbalance of Section 4. This can not rest on software solely: Bayesian vancomycin dosing still requires a serum concentration assay, itself inaccessible in several high-burden settings, so equity methods must treat laboratory and TDM capability as a co-equal constraint.

India illustrates both the difficulty and available system.ICMR‘s AMR Surveillance and Research Network has issued annual resistance-trend reports across a national tertiary-care network since 2013, structurally similar and comparable to the GLASS inputs of Section 5.4 [44,36]. India’s National Action Plan on AMR sets out a One Health management structure executed partially through NCDC monitoring [45,46]. Schedule H1 of the Drugs and Cosmetics Rules and the ‘Red Line’ campaign function as population-level levers a system-scale twin could treat as policy variables, significantly as the platform of Section 5.3 treats screening and separation [16]; and the Pharmacy Practice Regulations, 2015, officially recognise the clinical pharmacist‘s role in Indian ASPs, making a pathway for operationalising twin-informed dosing at the bedside [47].Set against this is the constraint noted above: TDM assay availability remains irregular across Indian

hospitals, and any deployment approach here must treat assay admittance, not software, as the binding constraint.

9. FUTURE DIRECTIONS

Several directions are probable and expected to shape the field‘s following phase: prospective, outcome-linked validation moving beyond proof-of-concept toward the standard already available for AUC-guided vancomycin dosing [22], extended to sepsis-forecasting, transmission, and policy-simulation twins; greater integration across the patient-, ward-, and system-level twins of Section 5; now separate lines of work; letting information flow between scales as envisioned in Figure 5;federated, privacy-preserving learning to reconcile digital twins ‘data-hungry nature with the management concerns of Section 8.2 [37,39]; closer integration of genomic and phenotypic monitoring data, developing on GLASS and the ICMR network of Section 8.4, so twins revise local resistance-prevalence assumptions as well as individual paths [1,2,16,36,44]; and deliberate design for lower-resource settings; lightweight, mobile-first, interoperable-by-default instruments; to reduce instead than reinforce worldwide AMR-mortality inequities [2,25,26,38].

10. CONCLUSION

Digital twin technology provides a conceptually distinct addition to the stewardship toolkit: a persistent, continuously updated, forward-simulating representation of a patient, ward, or condition system, closed-loop linked to its physical equivalent through real-time data. Digital twins have shifted from aerospace and production into initial but genuine clinical application; most maturely in Bayesian MIPD, most recently in hospital-scale AMR forecasting. This complements instead than substitutes existing digital decision support, and its evidence foundation remains significantly less mature. Realising its potential depends on sustained investment in data system, thorough and meticulous prospective validation, management tackling privacy and regulatory uncertainty, and attention to equitable deployment; preconditions, given the scale of the worldwide AMR strain, for translating an encouraging paradigm into quantifiable decreases in opposition and its human cost.

11. LIMITATIONS

This is a narrative alternatively than methodical and organized review. No protocol was recorded, screening was performed by a single reviewer instead than in identical and matching, and the search was restricted to English-language literature, potentially excluding relevant non-English reports from lower- and middle-income settings. A substantial part of the system-level evidence in Sections 5.3-5.4 rests on a

single unrefereed preprint [16], flagged at each citation and treated as initial pending peer review and replication. Finally, thisare a swiftly moving domain: multiple sources were issued within the twelve months preceding this review, and the evidence landscape is anticipated to move materially by publication.

CONFLICT OF INTEREST

The authors declare no known contending financial interests or personal connections that could have affected this work, and no relationship, financial or otherwise, with InsightRX or any other named commercial vendor of Bayesian dosing software; the common and nonspecific term 'commercially available Bayesian dosing software' is used throughout for this reason.

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AUTHOR CONTRIBUTIONS

K.P. and S.A.A. jointly conceived the review, conducted the literature search and screening, drafted the manuscript, and approved the final version.

ETHICS STATEMENT

Not applicable — this review did not involve human participants or animals.

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