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Is AI-driven drug forecasting feasible in Thailand?

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Artificial intelligence (AI) offers considerable potential to improve efficiency and resilience in pharmaceutical supply-chain management. Data-driven forecasting models that incorporate both endogenous and exogenous shocks within and beyond health systems can strengthen predictions of drug demand, reducing stockouts and overstocking. Improved forecasting may mitigate preventable morbidity, financial costs, and environmental waste associated with expired or emergency-procured medicines. In this Perspective, we outline Thailand's publicly funded pharmaceutical supply-chain architecture and assess its readiness for adopting AI-enabled drug-demand forecasting. Although complex, Thailand has a well-defined system for managing publicly funded medicines. However, we identify four key system-level barriers to the effective adoption of AI-enabled drug-demand forecasting in Thailand. These include (i) inconsistent drug coding and data standards; (ii) limited data integration and data sharing; (iii) fragmented and incompatible digital infrastructure; and (iv) gaps in ethical governance and regulatory preparedness. Addressing these structural constraints will be essential to realize the potential of AI-driven forecasting to strengthen performance of the pharmaceutical system in Thailand and similar settings.

KEYWORDS
artificial intelligence, drug-demand forecasting, health information systems, interoperability, pharmaceutical supply chain, Thailand

1 Introduction

Pharmaceutical supply chains are critical to ensure timely access to essential medicines. Yet, many health systems worldwide continue to face persistent inefficiencies such as stock imbalances, delayed deliveries, and premature expirations (Privett and Gonsalvez, 2014; Shukar et al., 2021). These challenges not only disrupt patient care but also increase operational costs and contribute to large-scale medicine wastage, which carries both economic and environmental consequences. Recent evidence suggests that the pharmaceutical sector contributes nearly a quarter of healthcare-related greenhouse gas emissions, with much of this impact linked to overproduction, inefficient distribution, and the improper disposal of unused medicines (Roy, 2021). The COVID-19 pandemic further exposed the fragility of these systems and highlighted the urgent need for more responsive, data-driven supply-chain solutions (Salahuddin et al., 2022; Prasertsri, 2024; Pathan and Ruangchoengchum, 2025).

Artificial intelligence (AI) has emerged as a promising tool to address these systemic challenges (Nuta et al., 2025; Kaur and Prakash, 2025; Hussain et al., 2024). AI can improve forecasting accuracy, streamline distribution, and strengthen supply-chain resilience by integrating and analyzing large, diverse datasets, often through near-real-time or regularly updated data pipelines. Several countries have implemented AI in pharmaceutical logistics and evidence shows that AI-enabled forecasting significantly lowers the costs, reduces shortages, and lessens environmental impact (India UNDP, n.d.; Indonesia UNDP, 2024; inSupply Health, 2024).

In Thailand, the use of digital health (including AI) to enhance health system efficiency has accelerated since the COVID-19 pandemic. However, its application in the pharmaceutical supply chain remains limited. Health facilities primarily rely on either historical procurement records or expert judgement to forecast drug demand. However, predicting drug demand has become increasingly challenging for two reasons. First, Thailand is vulnerable to climate change and the depth and breadth of its impact on health and health system is accelerating (Ratanawong et al., 2025). Second, to ensure timely access to care, Thailand introduced the “One ID” policy, which allows patients to receive care in any healthcare facility across the country whereas access was previously more closely tied to patients’ registered facilities (Srithamrongsawat et al., 2024; Office FA, n.d.). Addressing this challenge requires accurate and robust demand forecasting that can account for exogenous and endogenous shocks within and outside the health sector (Suchonwanich et al., 2020a; Suchonwanich et al., 2020b; Thammatacharee et al., 2020; HITAP, 2024). Therefore, we developed a prototype of an AI-enabled drug forecasting tool[1] using data from two hospitals in Thailand (Samniang et al., 2026). However, the accuracy, reliability, and effective adoption of such tools depend on several system-level factors.

In this Perspective, we examined the potential role of AI in pharmaceutical logistics and Thailand’s publicly funded pharmaceutical supply-chain architecture. Drawing on a targeted desk review, stakeholder consultation insights, and practical observations from prototype development, we identified system-level barriers that may affect implementation of AI-enabled drug-demand forecasting. Findings were interpreted in relation to selected thematic domains from the WHO European Region’s assessment of AI readiness for health systems to inform policy considerations for effective, equitable, and scalable implementation (Dunning et al., 2026).

2 Artificial intelligence in pharmaceutical supply chains

AI in the pharmaceutical supply chain involves using advanced computational tools such as machine learning (ML), deep learning, predictive analytics, and natural language processing to improve how medicines move from production to the point of care (Vadaga et al., 2025). By combining data from manufacturing, inventory, demand trends, and real-time environmental monitoring, AI enables more accurate, data-driven decisions in procurement, storage, and distribution. Unlike conventional forecasting approaches based largely on historical averages, AI can process large and diverse datasets to identify patterns, forecast demand, and adjust to exogenous shocks such as outbreaks or updated treatment guidelines (Al-Hourani and Weraikat, 2025; Sharma et al., 2025; Shen et al., 2024; Bhatt and Kumar, 2023). These capabilities make AI a transformative tool for optimizing the pharmaceutical supply chain.

ML plays a central role in this optimization. Supervised and unsupervised algorithms can forecast demand by analyzing historical usage, seasonal disease trends, and external factors such as weather or public health alerts. Reinforcement learning and genetic algorithms can then improve inventory parameters such as reorder points, safety stock, and allocation rules based on real-time supply and consumption data (Vadaga et al., 2025; Sharma et al., 2025). In distribution, AI-powered routing and scheduling algorithms adjust deliveries to account for traffic, weather, and urgency. Meanwhile, Internet of Things (IoT)-enabled systems use networks of connected sensors and devices to monitor cold chains and help ensure that temperature-sensitive medicines remain within safe limits (Vadaga et al., 2025; Shen et al., 2024).

Evidence from early adopters has shown the impact of AI-driven drug systems in strengthening their national drug supply chains. Tanzania’s AI drug forecasting system links central procurement and public facilities to improve stock availability and reduce waste (inSupply Health, 2024); India’s Electronic Vaccine Intelligence Network (eVIN) uses real-time stock and temperature data to improve vaccine logistics and reduce stockouts (India UNDP, n.d.); and Indonesia’s Sistem Monitoring Imunisasi Logistik secara Elektronik (SMILE) system applies AI and big data analytics to monitor vaccine logistics and prioritize underserved areas, leading to a 70% reduction in stock-outs within six months with an estimated return on investment (ROI) of 2.77 (Indonesia UNDP, 2024). In China, AI-assisted procurement systems have shortened delivery times by more than 20% by optimizing supplier performance and logistics coordination (Shen et al., 2024). For instance, AI-driven forecasting models have achieved up to a 22% reduction in supply chain costs and an 18% increase in delivery efficiency by optimizing demand predictions and improving supplier performance (Rishi et al., 2025). These cases highlight how AI can enhance efficiency, reduce waste, and strengthen resilience across diverse health system contexts. The WHO assessment of AI readiness in health systems also emphasizes that successful AI implementation requires system-level preparedness, rather than relying solely on technical model development (Dunning et al., 2026). Effective implementation therefore requires high-quality, interoperable data systems, secure technical infrastructure for data collection and analytics, skilled personnel for system design, validation, and oversight, clear governance and accountability mechanisms to safeguard privacy and ensure transparency, and sustained investment with cross-sector collaboration to support scale-up and long-term system maintenance (Vadaga et al., 2025; Al-Hourani and Weraikat, 2025; Shen et al., 2024; Bhatt and Kumar, 2023).

Understanding the potential role of AI in pharmaceutical supply chains provides a basis for examining Thailand’s public pharmaceutical system. Mapping how medicines are procured, stored, and distributed helps identify operational gaps and the conditions required for AI-enabled forecasting.

3 Approach and sources

Figure 1 presents the analytical framework used in this Perspective. We conducted a targeted, non-systematic desk review of academic literature, official reports, policy documents, and

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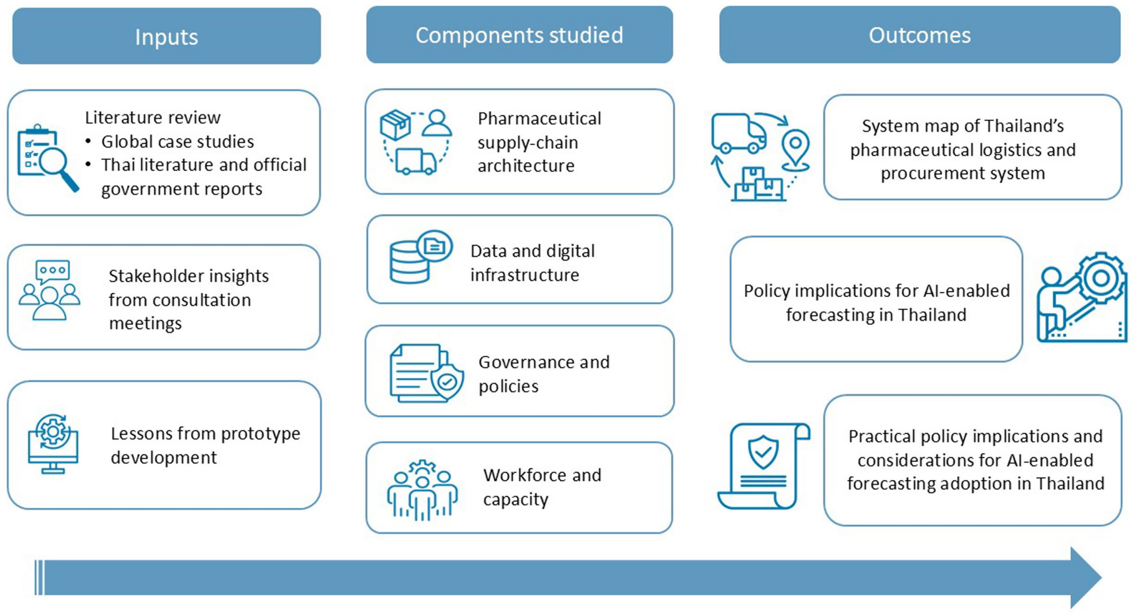

FIGURE 1
Analytical framework and sources used in this perspective.

technical materials on pharmaceutical procurement, public-sector logistics, digital-health systems, medicine data standards, and relevant policies. Sources were identified through academic databases, organizational websites, and reference-list checking and selected for their relevance to Thailand's publicly funded pharmaceutical system and to at least one component of the analytical framework.

We also drew on two stakeholder consultation meetings conducted between July and August 2025 as part of a separate AI-enabled drug-demand forecasting prototype study (Samniang et al., 2026). A total of five participants from the Government Pharmaceutical Organization (GPO) and two provincial hospitals in Lamphun were invited based on their involvement in pharmaceutical procurement, inventory, and supply management. Documentation relating to the Government Pharmaceutical Organization's participation in the prototype study is provided in Supplementary Material 2.

The consultations were not designed as formal qualitative study. Meeting notes were reviewed by the research team and were organized according to predefined topics, including current forecasting practices, data availability, drug coding, interoperability, data sharing, and implementation barriers (Supplementary Material 1). Findings from the desk review and consultation notes were combined through a structured narrative synthesis, in which information was compared across these topics and grouped into broader system-level themes. Practical challenges encountered during prototype development, particularly those related to data quality, drug coding, interoperability, data access, and integration with procurement workflows were used separately to contextualize these themes and are described in Section 4.2. The prototype served only as an illustrative implementation case; its development and performance evaluation are reported separately and were outside the scope of this Perspective. The resulting themes were then interpreted using relevant domains from the WHO European Region's AI-readiness assessment as a conceptual reference.

4 Results

4.1 Architecture of Thailand's public pharmaceutical system

Medicines listed in Thailand's National List of Essential Medicines (NLEM) are covered under three public health insurance schemes: (i) Universal Coverage Scheme (UCS); (ii) Civil Servant Medical Benefit Scheme (CSMBS); and (iii) Social Security Scheme (SSS) (Thai Drug System C, 2020; Disayanun, 2021; Tangcharoensathien, 2024). The NLEM is organized into categories A-E: A covers first-line medicines; B, second-line alternatives; C, specialist-prescribed medicines; D, medicines subject to specified restrictions; and E, medicines under special programs. Category E1 covers medicines for government special programs, while E2 covers high-cost medicines for specified condition (Thai Drug System C, 2020). In practice, these categories translate into two main procurement pathways for NLEM medicines:

- General NLEM drugs (A-D) are primarily procured at the hospital level. These include widely used, lower-cost medicines such as antibiotics, antihypertensives, and basic insulin. These are funded through capitation or Diagnosis-Related Group (DRG) payment systems and procured directly by hospitals from suppliers (Thai Drug System C, 2020; Disayanun, 2021).
- Special Drug Program (SDP) medicines (E1 and E2), which are high-cost or specialized treatments managed centrally by the National Health Security Office (NHSO), rather than procured directly by hospitals. These drugs, often used for rare diseases, cancer, or complex conditions, require prior authorization, registry enrollment, or fulfillment of specific clinical criteria. Examples include erythropoietin for dialysis patients and antiretrovirals for HIV (Thai Drug System C, 2020).

Non-NLEM drugs fall outside the essential list and are typically not reimbursed by public health schemes unless granted special

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approval. They may be funded through a hospital's internal budget or paid for out of pocket or through private insurance (Thai Drug System C, 2020; Sermsuk et al., 2021).

Figure 2 provides an overview of Thailand's pharmaceutical logistics system, with the pathway for SDP medicines indicated by green arrows. Based on findings from both the literature review and insights from the stakeholder consultations, hospitals request these medicines through their hospital information system (HIS), which connects directly to the NHSO's electronic claims (e-Claim) system for submitting outpatient and inpatient reimbursement claims. Hospitals also report their drug procurement data via systems such as the Drug and Medical Supply Information Center (DMSIC), particularly for antiretroviral medicines, dialysis solutions, and erythropoiesis-stimulating agents (Thai Drug System C, 2020; Tangcharoensathien, 2024).

DMSIC, operated by the Ministry of Public Health, monitors national medicine and medical supply usage and provides data to the NHSO for procurement planning and reimbursement under the UCS (Thai Drug System C, 2020; Tangcharoensathien, 2024). It also feeds information into disease management workflows and the e-Claim system, especially for antitoxins, antiplatelets, and other E2-category medicines. Orders recorded in the HIS are also transferred to hospital warehouse systems. For selected products, these systems connect to the Vendor Managed Inventory (VMI) platform, through which the GPO coordinates stock monitoring and delivery to health facilities or patients, particularly for dialysis products (Disayanun, 2021; Sermsuk et al., 2021).

In contrast, general NLEM drugs, shown in blue arrows, consist of low-cost essential medicines purchased directly by public hospitals from suppliers based on their internal procurement processes. Suppliers then deliver the medicines straight to the hospitals without central involvement from the NHSO (Thai Drug System C, 2020; Sermsuk et al., 2021).

Thailand's drug procurement and reimbursement system operates through two main pathways (Figure 3). For general NLEM medicines, hospitals procure medicines directly from suppliers, with inpatient costs reimbursed through a DRG-based payment arrangement within the hospital's annual budget (Thai Drug System C, 2020; Disayanun, 2021). In contrast, SDP medicines follow a more centralized pathway, where hospitals submit patient-level drug requests through NHSO-linked systems such as DMSIC, e-Claim, or VMI, depending on the drug category. These systems are connected to broader financial and reimbursement platforms, including the Financial Data Hub (FDH), which was recently updated to link with the NHSO's e-Claim system to support national-level financial management (National Health Security Office, 2024). For supplier selection, centrally procured medicines are overseen by NHSO through the Government Procurement System (e-GP), using criteria such as price, quality, and regulatory compliance (Disayanun, 2021). Approved suppliers deliver medications either to hospitals or directly to patients (Thai Drug System C, 2020; Disayanun, 2021; Tangcharoensathien, 2024). At the facility level, procurement decisions are guided by both strategic and operational mechanisms. Pharmacy and therapeutics committees (PTCs) support formulary and annual procurement planning, while routine ordering is typically managed by pharmacy inventory units using historical consumption data, stock-control parameters, and prioritization tools such as AB analysis or ABC–VEN analysis (Suchonwanich et al., 2020a; Umnuaypornlert and Kitikannakorn, 2014; Kritchanchai and Krichanchai, 2016; Rattanasiha, 2024; Yosprasit and Siengdee, 2024; Kaew-ngam, 2022). For some special program medicines, NHSO-linked systems support pre-authorization, purchase order generation, and replenishment to hospital warehouses within a short timeframe.

Despite this structured system, persistent challenges including stock imbalances, drug registration delays, and fragmented data flows, highlight the need for more responsive and real-time solutions (Suchonwanich et al., 2020a; Thammatacharee et al., 2020; Thai Drug System C, 2020). The ongoing integration of the FDH and e-Claim systems represents an important step forward; however, data harmonization across platforms remains a key barrier (Ministry of Public Health, 2025). The next section examines these barriers and considers how addressing them could support the effective use of AI in Thailand's pharmaceutical supply chain.

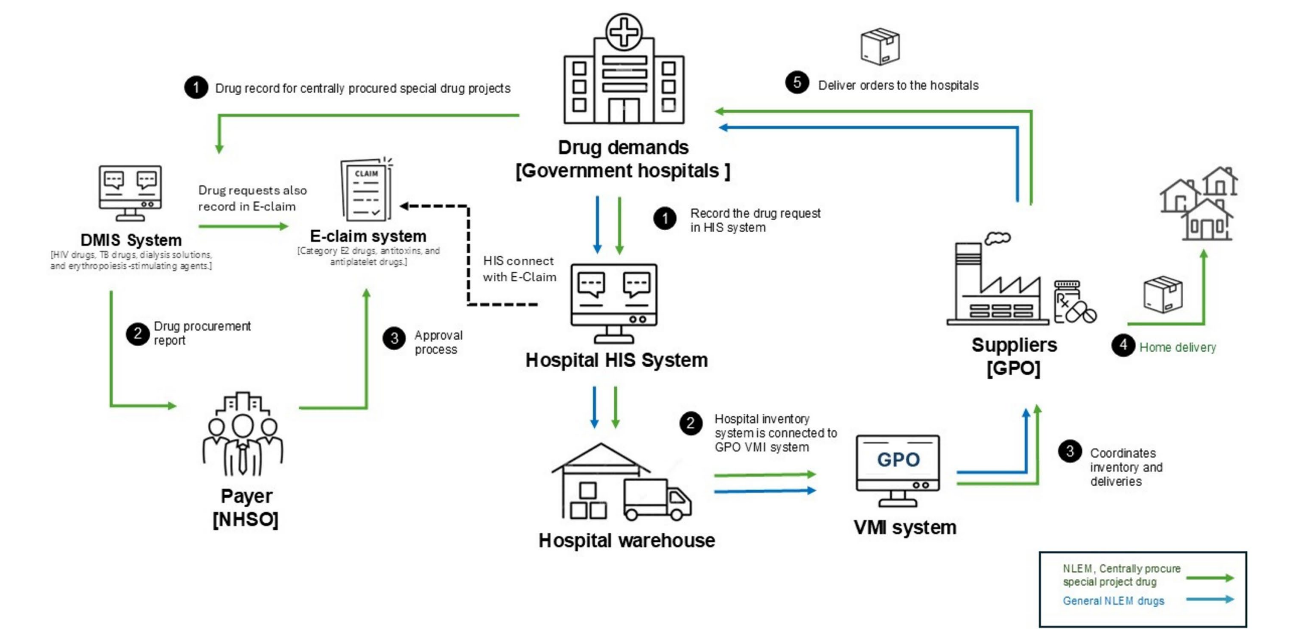

FIGURE 2
Landscape of Thailand's pharmaceutical logistics system.

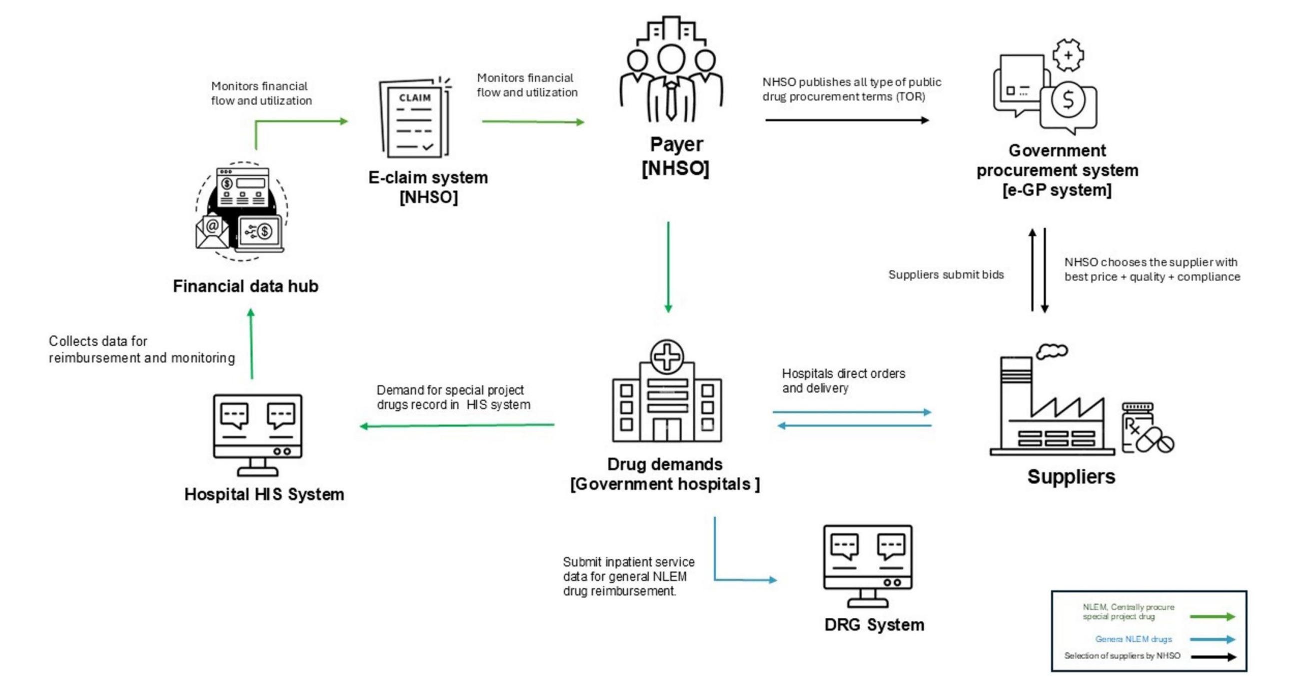

FIGURE 3
Drug reimbursement and financial flows under Thailand's Universal Coverage Scheme.

4.2 Key barriers to AI adoption in drug forecasting

4.2.1 Data readiness: inconsistent drug coding and data standards

At the core of AI readiness is access to interoperable and timely data. However, Thailand continues to use multiple drug coding systems, including the 24-digit code developed by the Thai Health Coding Center (THCC), Thai Medicines Terminology (TMT), Anatomical Therapeutic Chemical (ATC) codes, and Global Trade Item Numbers (GTINs) (Suchonwanich et al., 2020b; Kijsanayotin et al., 2016). Although TMT adoption is increasing, major databases such as the Health Data Center (HDC) still rely on the 24-digit code, while newly registered medicines may not yet have TMT codes, creating further fragmentation (Kijsanayotin et al., 2016). Similar challenges were observed during prototype development, where the same medicine sometimes appeared under different local descriptions or internal hospital codes, requiring additional cleaning and code mapping. The absence of a unified and regularly updated medicine database therefore remains a major barrier to AI readiness and forecasting accuracy. In response to these challenges, Thailand has introduced a five-year Identification of Medicinal Products roadmap to improve coding standardization, although implementation is still ongoing (Thai Food and Drug Administration, 2023). Shortages of skilled information technology (IT) personnel in operational and managerial roles may further delay the implementation and governance of national health-information systems (Suchonwanich et al., 2020b).

4.2.2 Data governance and access: limited integration and data sharing

In Thailand, data sharing across the health sector is often slow and complex due to limited coordination across institutions and ministries, as well as extensive administrative procedures. Although procurement and reimbursement data are available through several systems and reports (Figure 3), there is no integrated platform that tracks medicines across procurement, delivery, use, and reimbursement under the UCS. Unlike centralized platforms such as OpenSAFELY in the United Kingdom, the All of Us Research Program in the United States, and France's Health Data Hub, Thailand lacks a unified infrastructure for standardized data exchange across key stakeholders (Bennett Institute for Applied Data Science, 2020; National Institutes of Health, n.d.; Health Data Hub, 2019). Similar challenges were encountered during prototype development, where access to relevant hospital data required institution-specific coordination and approval, while data were stored in separate systems and formats, limiting automated exchange and regular updates. These constraints are compounded by shortages of skilled personnel and limited awareness of AI tools, as reported in the Thailand AI Readiness Survey 2023 (NSTDA Agency, 2023). Moreover, if forecasting models incorporate external drivers such as weather, air pollution, disasters, developing accurate and robust forecasts will require additional data-sharing arrangements with relevant non-health agencies.

4.2.3 Digital infrastructure and implementation readiness

Thai hospital-level forecasting currently relies mainly on historical dispensing or procurement data, simple consumption trends, and established ordering cycles. These approaches may be inadequate during disease outbreaks, changes in clinical guidelines, or supply-chain disruptions (Suchonwanich et al., 2020a; Suchonwanich et al., 2020b). On the supply side, organizations such as GPO and private vendors develop separate forecasting tools that operate in silos and are not integrated with hospital systems. Further complicating forecasting efforts is the diversity of hospital HIS systems used across different hospital-levels points raised during the stakeholder meeting.

Secondary and tertiary hospitals often use Hospital information System xP (HOSxP), which features its own drug coding and requires mapping to standardized formats like the Thai Medicines Terminology (TMT) (Sarutiyapithorn et al., 2015). Primary care units and subdistrict health-promoting hospitals commonly use the open-source Java Health Center Information System (JHCIS) (Sarutiyapithorn et al., 2015; Ministry of Public Health Thailand, 2017) while other institution have developed their own HIS platforms such as the Hospital Administrative Information Technology (HAIT) system, which may connect directly with NHSO and potentially the Food and Drug Administration (FDA) (Vachira Phuket Hospital, n.d.). Consultation and prototype-development (Samniang et al., 2026) insights indicated that hospitals also rely on numerous in-house and vendor-developed platforms beyond these major systems. This fragmented digital infrastructure poses a significant barrier to establishing a unified, national-level forecasting system that can support timely and coordinated medicine distribution.

4.2.4 Governance and regulatory readiness: ethical safeguards, accountability and trust

As interest in AI continues to grow, ethical and governance considerations are becoming central to discussions around its application in healthcare. AI-enabled forecasting may requires access to patient-level or commercially sensitive facility-level data, raising critical questions under Thailand's Personal Data Protection Act (PDPA) (HITAP, 2024). At the same time, evidence from Thailand's health-system AI landscape indicates that governance and regulation remain critical enabling conditions, with challenges including gaps in legal and institutional frameworks that may hinder safe adoption (HITAP, 2025). At present, there is no formal national governance framework to guide the use of AI in healthcare logistics, creating further uncertainty for stakeholders.

Concerns are also growing around the adoption of foreign regulatory models such as the European Union's AI Act, without sufficient localization, which could result in overregulation and delay the practical deployment of AI tools (Orlowski, 2024). While initiatives like the AI Governance Clinic (AIGC), led by the Electronic Transactions Development Agency (ETDA), are working to develop cross-sectoral AI governance guidelines, these efforts remain in early stages and have yet to be implemented at scale or integrated into healthcare logistics systems (NSTDA Agency, 2023; Saffa, 2023). Without clear governance and coordination, these gaps may undermine compliance with Good Distribution Practice (GDP) requirements and weaken institutional and public trust in AI applications for pharmaceutical logistics.

5 Policy implications of targeted strategies

Thailand's transition toward AI-enabled drug-demand forecasting is constrained by interconnected challenges in data systems, governance, workforce capacity, and implementation readiness. Many of these issues may also apply to other low- and middle-income countries facing similar health-system and digital-readiness constraints. To structure the interpretation, the Thailand-specific findings were considered in relation to six domains from the WHO European Region's AI-readiness assessment (Dunning et al., 2026), which was used as a conceptual reference rather than as a formal tool to assess or benchmark Thailand (see Table 1).

Based on this interpretation, this Perspective proposes six strategies for Thailand that may also be relevant to other LMICs facing similar digital-health and pharmaceutical supply-chain challenges:

- Clarify national direction and oversight: define agency roles, shared priorities, and responsibility for coordinating AI-enabled pharmaceutical forecasting.
- Build workforce and user capacity: train pharmacists, procurement personnel, IT personnel, data scientists, managers, and regulators, while involving end users throughout system design.
- Strengthen governance and accountability: establish clear guidance on privacy, model validation, human oversight, transparency, cybersecurity, and auditing.
- Improve data foundations: harmonize medicine coding systems, strengthen interoperability, establish an authoritative medicine database, and improve data-sharing arrangements.

TABLE 1 WHO AI-readiness domains and Thailand-specific findings.

WHO AI-readiness domain	Relevant to the Thailand-specific findings
1 Strategy and oversight	Thailand has broader AI and digital-health initiatives, but AI-enabled pharmaceutical forecasting requires clearer coordination, defined institutional roles, shared priorities, and stronger oversight mechanisms.
2 Stakeholders and workforce	Shortages of skilled IT personnel, limited AI expertise, and gaps in implementation capacity may affect system development, validation, and routine use. Consultations also emphasized the need to involve operational users throughout system design and implementation.
3 Legal and policy structures	Uncertainty remains around data privacy, accountability, model validation, auditing, and the absence of national guidance specific to AI use in pharmaceutical logistics.
4 Health-data governance	Multiple medicine coding systems, fragmented hospital and national databases, limited interoperability, and complex data-sharing procedures reduce data consistency, accessibility, and readiness for AI-enabled forecasting.
5 AI for health-system needs	AI-enabled forecasting could help manage stock imbalances, disease-related changes in demand, patient mobility, and supply disruptions. However, forecasting output must be designed to fit existing inventory, budgeting, and procurement, and approval workflows.
6 Adoption barriers	Scale-up is constrained by interconnected gaps in data quality, interoperability, workforce capacity, governance, financing, and long-term institutional support.

- Use phased implementation: test practical use cases in representative hospitals and medicine categories before wider scale-up.
- Ensure long-term sustainability: secure stable financing, clear institutional ownership, ongoing maintenance, and collaboration across government, hospitals, academia, and technology partners.

These strategies may be transferable to health systems facing fragmented data, limited interoperability, workforce constraints, and governance gaps. However, their implementation should be adapted to country-specific financing arrangements, procurement pathways, medicine coding systems, institutional mandates, and digital infrastructure.

6 Limitations

This Perspective has several limitations. The targeted desk review may not have captured all relevant evidence, and the small, purposively selected stakeholder group may not represent all public- and private-sector pharmaceutical supply-chain actors in Thailand. The prototype was developed using data from a limited hospital context; therefore, the observed challenges may vary across facilities, regions, information systems, and medicine categories. Nevertheless, combining documentary evidence, stakeholder insights, and prototype-development experience provides a useful system-level perspective on AI-enabled drug-demand forecasting in Thailand.

7 Conclusion

Thailand's system for managing publicly funded medicines is complex but has clearly defined procurement and reimbursement pathways. However, making the pharmaceutical supply chain more resilient to shocks requires leveraging data and innovation tools like AI-enabled drug forecasting. While the appetite for implementing digital solutions within the health sector is increasing, Thailand needs to invest time and resources in creating strong foundations upon which solutions like AI can maximize impact and broaden use cases.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and the institutional requirements.

Author contributions

YT: Project administration, Writing – original draft, Formal analysis, Resources, Data curation, Visualization, Conceptualization, Validation, Investigation, Writing – review & editing, Methodology. WS: Investigation, Visualization, Methodology, Conceptualization, Writing – review & editing, Validation, Resources, Supervision. AM: Investigation, Writing – review & editing, Validation, Resources. SS: Investigation, Writing – review & editing, Validation, Resources. SK: Supervision, Methodology, Conceptualization, Visualization, Validation, Resources, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2026.1825613/full#supplementary-material

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