

Artificial Intelligence for Supply Chain and Survival in Biological and Climatic Health Emergencies

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ABSTRACT

Low- and middle-income countries continue to grapple with the challenges of demand forecasting, managing stock, and providing access to essential commodities on a timely basis. Our engagement in Pakistan has been active since 2009, when we started developing country's health supply chain infrastructure with the design and implementation of the Vaccine Logistics Management Information System (VLMIS) for national and provincial entities of Expanded Programme on Immunization (EPI). We have systematically incorporated Artificial Intelligence (AI), business intelligence and machine learning (ML) into vaccine preventable infectious diseases (VPID) and supply chain processes over the past eleven years. This vision paper delineates how we aim to incorporate AI into the science of implementation, with a keen eye on integrating AI into the real world, stakeholder co-design, and continuous performance optimization. Using examples of case studies, such as supply chain and logistics for the sciences of preventing Measles and Polio re-emergence of 2012-13, and loss of \$3.4 million pentavalent vaccine in 2015, forecasting and quantification of PPE (personal protective equipment) and vaccines in 2022, design and deployment of Pakistan's first Travelers Surveillance Information System. We contributed to strengthening the backbone of health systems notably international standards of supply chain strategic planning, procurement and forecasting and supply planning (FASP), commodity security, workforce management, warehousing, storage and distribution planning and execution. The latest AI-based contraceptive forecasting in Balochistan, Gilgit-Baltistan, AJ&K and Islamabad and vaccine demand forecasting in Pakistan, we can illustrate how practical AI can enhance global health security, pandemic preparedness, and health response to emergencies. In parallel, academic collaborations, especially through the Applied AI in Healthcare course (BMES-826) at National University of Science and Technology (NUST), have involved graduate students in forecasting models, optimization models, and early-warning systems based on real-time data. Such scholarly training has been used to inform operational planning and built local technical capacity on AI in health supply chains. This framework places AI not as an independent innovation but a ubiquitous system-wide enabler, aligning data science with operational conditions to produce resilient, proactive, and equitable health systems.

BACKGROUND

We started our supply chain system journey in 2009, and the national turnaround of VLMIS-

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a digital platform that revolutionized the transparency of vaccine stock and informed evidence-based procurement. With this digital base established, we have increasingly employed AI-powered forecasting and analytics in public health initiatives, directly linking machine learning results with policy and practice. Such development has been informed by the pillars of implementation science, to make technological innovation based on viability, acceptability, and

scalability.

AI FOR PREVENTIVE HEALTH INTERVENTIONS

Preventive health thrives on anticipation: predicting needs, preempting shortages, and mobilizing resources before service disruptions occur. Using AI-driven FASP analysis, we have been able to identify supply bottlenecks, optimize resource allocation, and align commodity distribution with service delivery demand. In Balochistan, predictive modelling for the self-injection rollout of DMPA-SC (subcutaneous depot medroxyprogesterone acetate) ensured uninterrupted contraceptive availability, reduced wastage, and expanded access to modern family planning methods. These models provided actionable intelligence for procurement planning, inventory control, and last-mile delivery.

APPLIED AI IN ACADEMIC AND OPERATIONAL ECOSYSTEMS

Students have implemented AI algorithms into EPI datasets under the supervision of a Professor of Data Sciences and Practices at School of Mechanical and Manufacturing Engineering (SMME), NUST, leading to five-year vaccine demand projections used to guide procurement, cold chain expansion, and budgeting activities. Such blending of operational realities and academic innovation enhances technical capacity and evidence-based decision-making in the field of public health. Within this framework, projects have addressed diverse vaccine supply chain challenges nationwide: optimizing bOPV (bivalent oral polio vaccine) consumption to reduce district-wise disparities in Karachi; developing GaviOptima, an AI-powered forecasting and distribution tool; creating an early-warning system for Measles-2 coverage decline; and conducting AI-driven analyses of polio and TB (tuberculosis) vaccine consumption to uncover inefficiencies. Other initiatives have mapped Hepatitis-B vaccine outreach gaps in Punjab, refined provincial planning using population growth and wastage data, and produced multi-year forecasts for

PCV13 (13-valent pneumococcal conjugate vaccine) and Pentavalent-1 in Punjab and Sindh. Policy-focused forecasts have guided provincial leadership, while optimization models have improved Hepatitis-B vaccine allocation in Sindh. Collectively, these initiatives show how FASP analysis, predictive modelling, and optimization algorithms developed in academic settings can be embedded into real-world decision-making, ensuring AI solutions are both technically robust and programmatically relevant.

RELEVANT ACHIEVEMENTS SUPPORTING AI INTEGRATION

The initiatives encompassed diverse health system strengthening measures, including the development of COVID-19 digital platforms for traveler surveillance, inventory management, and PPE forecasting calculators; commodity and cold chain support through the deployment of mobile biosafety laboratories, refrigerated transport, and oxygen commodity tracking with data-enabled monitoring; health data digitization efforts such as LMIS contraceptive analysis from 2011–2021, the DRAP (Drug Regulatory Authority of Pakistan) import/export licensing system, and integration of infectious disease platforms; and the application of AI-enhanced forecasting models to improve vaccine demand projections, procurement efficiency, and stock availability.

IMPLEMENTATION SCIENCE AND APPLIED AI FRAMEWORK

Our implementation science-based AI adoption framework emphasizes stakeholder co-design through the active inclusion of policymakers, logisticians, and health workers to promote contextual applicability. It uses iterative validation, comparing the outputs of predictive efforts in both historical and live data sets to ensure accuracy and alignment of policies. Capability development is pivotal, and training would focus on addressing mutual competencies between public health professionals and AI experts for sustained use. Embedded feedback loops are also part of the framework, where the operational outcomes are used to optimize

algorithms and make them more adaptable over time. This approach ensures AI is not an isolated pilot but a sustainable, embedded function within national health systems.

CONCLUSION

Our vision is a preventive health and supply chain ecosystem driven by AI that facilitates real-time detection of demand changes, supply bottlenecks, and preliminary signs of outbreaks, using predictive allocation to avoid shortages and surpluses. Our efforts build on World Health Organization (WHO) three pillars of prevention, detection and response and contributes locally as well as globally towards survival in biological and climatic health emergencies and pathogens of high concerns while supporting WHO, Preparedness and Resilience for Emerging Threats (PRET), Global Outbreak Alert and Response Network (GOARN), Pandemic Influenza Preparedness (PIP), International Pathogen Surveillance Network (IPSN). These efforts are to further

the integration of National Institutes of Health (NIH), Global Fund for AIDS, TB and Malaria (GFATM), Gavi Vaccine Alliance, FCDO (Foreign, Commonwealth & Development Office), Gates and USAID (U.S. Agency for International Development) funded information systems to achieve resilience, preparedness and Service Delivery Network Optimization for priority health areas like Family Planning (FP), Maternal, Neonatal and Child Health (MNCH), Nutrition, Infectious Diseases (IDs) and Immunization programs. This system will enhance resilience to pandemic, climate-related disruptions, and other emergencies through integrated platforms that combine procurement, warehousing, distribution, and service delivery data. This approach integrates expertise in deep supply chains with applied artificial intelligence and implementation science, enabling health systems to move beyond simply responding to crises to being proactive, using data and delivering public health in a sustainable way.