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BUILDING PREDICTIVE MODELS TO GUIDE PREPAREDNESS INVESTMENTS AND RISK FINANCING MECHANISMS IN PAKISTAN

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ABSTRACT

Background: The coronavirus disease 2019 (COVID-19) pandemic exposed significant vulnerabilities in public health systems globally, particularly in low and middle-income countries like Pakistan. In response, predictive modeling has emerged as a critical tool to guide proactive pandemic preparedness, optimize resource allocation, and strengthen risk financing mechanisms. This study aimed to develop and validate predictive models tailored to the Pakistani context and to support evidence-based decision-making for future health emergencies.
Methods: A mixed-methods approach was employed, integrating epidemiological forecasting, healthcare capacity modeling, cost-effectiveness analysis, and risk financing simulations. Data was sourced from multiple national institutions including the National Institute of Health (NIH), Lady Health Workers (LHW) Program, SehatSahulat Program (SSP), and also from international databases such as WHO and World Bank. Compartmental SEIR models and machine learning algorithms were used for outbreak forecasting. Discrete-event simulation (DES) assessed the healthcare system readiness under varying outbreak intensities. Economic evaluation was conducted using a Markov model to compare interventions. Stakeholder engagement informed policy relevance and implementation pathways.
Results: Epidemiological models demonstrated high accuracy in predicting dengue and SARS-CoV-2 outbreaks, with an average prediction error (MAE) of ±6.8%. Healthcare capacity analysis revealed significant shortages during severe scenarios: ICU beds fell short by 71%, ventilators by 75%, and medical staff by 58%. Targeted vaccination emerged as the most cost-effective intervention, yielding 2.3 million DALYs averted at $280 million, followed by mass testing. Risk financing simulations indicated that a hybrid mechanism combining contingency reserves and catastrophe

bonds could reduce unmet funding needs by up to 82%. Qualitative feedback from policymakers confirmed strong support for predictive analytics; it also highlighted existing challenges related to data interoperability and lack of technical capacity.
Conclusion: Predictive modeling offers a robust framework for enhancing pandemic preparedness and guiding risk financing decisions in Pakistan. By leveraging local data and global modeling techniques, this study provides actionable insights for improving healthcare resilience, optimizing resource use, and strengthening fiscal preparedness. Institutionalizing predictive analytics within national health planning is essential to make an effective transition from reactive crisis management to proactive; also data-informed strategies have capability of mitigating the impact of future pandemics.

INTRODUCTION

The global health landscape has undergone significant transformation in recent years, particularly in the wake of the coronavirus disease 2019 (COVID-19) pandemic. As one of the most severe public health emergencies of the 21st century, the pandemic not only exposed the vulnerabilities of healthcare systems worldwide but also highlighted the critical need for data-driven decision-making in resource allocation, outbreak forecasting, and financial preparedness. In low- and middle-income countries (LMICs), such as Pakistan, where healthcare resources are limited and economic resilience is constrained, the development and application of predictive modeling tools have emerged as essential necessity of modern pandemic preparedness strategies. Predictive models using historical, real-time, and simulated data offer policymakers and public health officials the ability to anticipate disease outbreaks, optimize healthcare delivery, and guide risk financing mechanisms that can mitigate both health and economic impacts during crises (World Bank, 2022; WHO, 2023).

Predictive modeling encompasses a range of analytical techniques, including epidemiological forecasting, statistical regression, machine learning algorithms, and agent-based simulations, all aimed at projecting future outcomes based on existing data patterns. These models have been increasingly utilized by national and international health agencies to understand transmission dynamics, assess intervention effectiveness, and allocate resources efficiently. During the height of the COVID-19 pandemic, countries that employed robust modeling frameworks, such as South Korea and Germany, demonstrated more effective containment measures and reduced mortality rates compared to those with reactive approaches (Liu et al., 2021). However, in many LMICs including Pakistan, the integration of predictive analytics into public health planning remains underdeveloped, often due to fragmented data systems, lack of preparedness including technical expertise, and insufficient institutional capacity (Khan et al., 2021; Abbas et al., 2022).

Pakistan, with a population exceeding 240 million and a diverse demographic and geographic profile, faces unique challenges in managing infectious disease outbreaks. The country experiences recurrent epidemics of dengue, malaria, cholera, and polio, alongside an increasing burden of non-communicable diseases. Additionally, climate change and environmental degradation have contributed to the emergence and re-emergence of vector-borne and zoonotic diseases, further complicating the public health landscape (Iqbal et al., 2020; Ahmed et al., 2023). In addition to these challenges, the nation's public health infrastructure remains under-resourced, with per capita health expenditure among the lowest globally (~$40 annually). This situation underscores the importance of leveraging predictive modeling to guide strategic investments in healthcare preparedness and financial sustainability (Government of Pakistan, 2021; World Bank, 2023).

The role of predictive modeling in pandemic preparedness extends beyond forecasting disease spread. It also plays a crucial role in estimating healthcare capacity needs, evaluating cost-effectiveness of interventions, and designing risk financing mechanisms. For instance, compartmental models like the Susceptible–Exposed–Infectious–Recovered (SEIR) framework have been used to simulate hospital bed requirements, ICU admissions, and ventilator availability under various outbreak scenarios (Rajpurkar et al., 2022). The effectiveness of SIER model can further be enhanced taking advantage of techniques like economic evaluationmodels, including cost-effectiveness analysis (CEA) and budget impact analysis (BIA), which provide valuable insights into the relative value of different public health interventions, enabling decision-makers to prioritize cost-efficient strategies in resource-constrained settings (Gopalani et al., 2021; Malik et al., 2022). In context of Pakistan where hospitals frequently face shortages of intensive care resources, such models could inform preemptive and mobilization of medical supplies.

Risk financing, another critical component of pandemic preparedness, involves the establishment of contingency funds, insurance schemes, and innovative financial instruments designed to provide rapid liquidity during health emergencies. Predictive analytics supports this process by quantifying outbreak probabilities, expected losses, and optimal funding thresholds. For example, catastrophe bonds and contingent credit facilities have been successfully deployed in regions prone to natural disasters, and similar mechanisms could be adapted for health emergencies in Pakistan. Modeling can estimate the likelihood of outbreaks based on historical trends and environmental variables, thereby guiding the design and activation of appropriate financial instruments (Gavi, 2021; IMF, 2022).

Despite the growing body of evidence supporting the use of predictive modeling in public health, several barriers hinder its adoption in Pakistan. One major challenge is the lack of centralized, interoperable data systems that can feed into predictive models. While provincial governments collect health-related data through initiatives such as the Lady Health Workers (LHW) program and the Sehat Sahulat Program (SSP), there is limited coordination between these systems, resulting in siloed information that undermines the accuracy of forecasts (Hussein et al., 2021; Qureshi et al., 2023). Additionally, the absence of a dedicated unit within the federal health ministry responsible for data science and modeling limits the institutional capacity to develop and implement predictive tools at scale.

Another key limitation is the shortage of trained personnel in the fields of epidemiology, biostatistics, and computational modeling. While academic institutions such as Aga Khan University and Health Services Academy offer training in public health, there is a pressing need for specialized curricula focused on digital health, machine learning, and health economics. Partnerships with international organizations, including the World Health Organization (WHO), the London School of Hygiene & Tropical Medicine (LSHTM), and the Institute for Health Metrics and Evaluation (IHME), can help bridge this gap through collaborative research, knowledge transfer, and technical assistance (Zaidi et al., 2021; Jooma et al., 2022).

Moreover, political instability and lack of policy integration remain critical factors in the successful implementation of predictive modeling frameworks. While the National Disaster Management Authority (NDMA) and the Emergency Operations Center (EOC) for

Polio/Pandemic Response have made strides in coordinating emergency responses, there is no formal mechanism for integrating model-derived insights into national preparedness plans. Establishing a National Pandemic Modeling Unit under the Ministry of National Health Services, Regulations & Coordination could serve as a central hub for generating, validating, and disseminating predictive insights to relevant stakeholders and institutions (Ali et al., 2023; Farooq et al., 2023).

Recent studies have emphasized the potential benefits of predictive modeling in enhancing public health outcomes in LMICs. A 2022 review published in Global Public Health found that countries employing predictive analytics experienced faster containment of outbreaks, better resource allocation, and lower mortality rates compared to those relying on reactive measures (Nisar et al., 2022). Similarly, a modeling study conducted in Bangladesh demonstrated how forecasting tools could improve vaccine distribution strategies during seasonal influenza surges, leading to a 20% reduction in preventable deaths (Hasan et al., 2021). These findings underscore the relevance of such approaches for Pakistan, where proactive planning could significantly reduce the burden of recurring epidemics.

Furthermore, the integration of climate and environmental data into predictive models presents an opportunity to anticipate and respond to emerging threats linked to climate change. With rising temperatures and erratic rainfall patterns, Pakistan has seen an increase in mosquito-borne diseases such as dengue and chikungunya. By incorporating satellite imagery, temperature trends, and precipitation data, predictive models can forecast high-risk areas and guide targeted interventions such as larval control and community awareness campaigns (Malik et al., 2021; Iqbal et al., 2023).

Hence, the emphasis is to analyze andintegrate the predictive models to generate effectivemodelling tasks to improve health care outcomes.

MATERIALS AND METHODS

Study Design: This study employed a mixed-methods approach, integrating quantitative predictive modeling with qualitative stakeholder insights, to develop a framework for guiding pandemic preparedness investments and risk financing mechanisms in Pakistan. The primary focus was on building and validating epidemiological forecasting models, economic evaluation models, and risk financing simulations using both historical and real-time public health data.

The study was conducted in three phases:

1. Data Collection and Preprocessing
2. Model Development and Validation
3. Policy and Stakeholder Engagement

All analyses were performed using open-source statistical software (R v4.3.1) and Python (v3.9), with visualization tools including Tableau and Power BI.

Data Sources: Data were collected from multiple national and international sources to ensure comprehensiveness and relevance to the Pakistani context:

1. Epidemiological Data:

a. National Institute of Health (NIH), Pakistan: Historical outbreak records for dengue, polio, influenza, and cholera (2018–2023).
b. Emergency Operations Center (EOC) for Polio/Pandemic Response: Real-time surveillance data during the SARS-CoV-2 pandemic.
c. World Health Organization (WHO) Disease Outbreak News: Global trends and regional comparisons.

2. Demographic and Socioeconomic Data

a. Pakistan Bureau of Statistics (PBS): Population distribution, age structure, and urbanization rates.

b. PSLM (Pakistan Social and Living Standards Measurement Survey): Poverty levels, access to healthcare, and education indicators (latest available: 2022–2023).

3. **Climate and Environmental Data**
   a. Pakistan Meteorological Department (PMD): Temperature, rainfall, and humidity data (2018–2023).
   b. NASA Earth data: Satellite imagery and land surface temperature for vector-borne disease mapping.
4. **Health System Capacity Data**
   a. Lady Health Workers (LHW) Program Reports
   b. Sehat Sahulat Program (SSP) Database
   c. Provincial Health Departments: Hospital bed availability, ICU capacity, and staffing levels.
5. **Economic and Financial Data**
   a. Government of Pakistan, Ministry of Finance: Budget allocations for health (2018–2023).
   b. World Bank Open Data: Per capita health expenditure, GDP growth, and poverty headcount ratio.
   c. Gavi – The Vaccine Alliance: Vaccine procurement and cost data.

Model Development

1. **Epidemiological Forecasting Models: A** compartmental SEIR (Susceptible–Exposed–Infectious–Recovered) model was developed to simulate disease transmission dynamics under various scenarios. Parameters such as basic reproduction number (R_0), incubation period, infectious period, and case fatality rate were calibrated based on historical outbreaks in Pakistan.

Additional sub-models included:

2. Age-structured modeling to assess differential impacts across population groups.
3. Mobility-adjusted modelsusing mobile phone data (where available) to simulate inter-district spread.
4. Machine learning algorithms (Random Forest, Gradient Boosting, and LSTM neural networks) were also trained on time-series outbreak data to improve forecasting accuracy.

2. Healthcare Capacity Modeling

A discrete-event simulation (DES) model was constructed to estimate surge requirements for hospital beds, ICU units, ventilators, PPE, and human resources under varying outbreak intensities. Inputs included:

a. Baseline hospital infrastructure
b. Daily admission rates
c. Length of stay
d. Vaccination coverage

Scenarios were simulated for:

a. Mild outbreak (e.g., seasonal flu)
b. Moderate outbreak (e.g., localized dengue surge)
c. Severe outbreak (e.g., second wave of pandemic)

3. Cost-Effectiveness Analysis (CEA)

An economic evaluation was conducted using a Markov model to compare the cost-effectiveness of different interventions:

a. Lockdown measures
b. Mass testing campaigns
c. Targeted vaccination strategies
d. Contact tracing and quarantine protocols

Key outcomes measured were:

a. Incremental cost per life-year saved
b. Disability-adjusted life years (DALYs) averted
c. Cost per infection prevented

Uncertainty was assessed through probabilistic sensitivity analysis (PSA) using Monte Carlo simulations.

4. Risk Financing Mechanism Modeling

A stochastic financial model was developed to estimate:

a. Expected outbreak-related costs over a 5-year horizon
b. Optimal size of contingency reserves
c. Feasibility of catastrophe bonds and contingent credit facilities

Key inputs included:

a. Historical outbreak frequency and severity
b. Inflation-adjusted unit costs
c. Government budget envelopes

Monte Carlo simulations were run to evaluate funding gaps under different preparedness scenarios.

Statistical Analysis

All statistical analyses were performed using R and Python packages:

a. Statsmodels, forecast, and prophet for time-series forecasting
b. deSolve and pomp for compartmental modeling
c. survival and flexsurv for survival analysis
d. rstan and brms for Bayesian calibration of model parameters

Descriptive statistics were computed for baseline variables. Multivariate regression models were used to identify predictors of outbreak severity and intervention effectiveness.

RESULTS

The predictive models developed in this study demonstrated significant potential in forecasting disease outbreaks, estimating healthcare resource requirements, evaluating intervention cost-effectiveness, and guiding risk financing strategies in Pakistan. Using historical outbreak data from 2018 to 2023, the SEIR compartmental model effectively simulated transmission dynamics of dengue and SARS-CoV-2. The basic reproduction number (R_0) was estimated at 1.5 (95% CI: 1.2–1.7) for dengue and 2.8 (95% CI: 2.4–3.2) during the peak of the third wave of the pandemic. Model validation using holdout datasets showed an average prediction error (MAE) of ±6.8%, indicating good accuracy in forecasting weekly case counts across Punjab and Sindh provinces. Machine learning-based forecasting models, particularly Random Forest and Long Short-Term Memory (LSTM), outperformed traditional time-series approaches in predicting dengue surges linked to monsoon rainfall, achieving an R^2 score of 0.89 and RMSE of 4.2 cases per 100,000 population.

Healthcare capacity modeling using discrete-event simulation (DES) revealed substantial mismatches between existing infrastructure and projected surge needs under moderate-to-severe outbreak conditions. As shown in Table 1, hospital beds, ICU units, ventilators, and medical staff were all found to be significantly inadequate during high-intensity scenarios, with shortages ranging from 57% to 75%. These findings underscore the urgent need for strategic investments in healthcare infrastructure, especially in densely populated urban centers such as Karachi and Lahore.

Table 1. Healthcare capacity shortfall under severe outbreak scenario.

Resource	Baseline Availability	Peak Demand (Severe Scenario)	Shortfall (%)
Hospital beds	1.2/1,000 population	2.8/1,000	57%
ICU beds	0.2/1,000 population	0.7/1,000	71%
Ventilators	0.05/1,000 population	0.2/1,000	75%
Medical staff	0.5 physicians/1,000	1.2 physicians/1,000	58%

The economic evaluation using a Markov model identified targeted vaccination as the most cost-effective public health intervention, yielding 2.3 million DALYs averted at an incremental cost of $280 million. Mass testing also demonstrated strong value, with 2.1 million DALYs averted at $320 million. In contrast, lockdown measures were less efficient, with only 1.2 million DALYs averted at a cost of $450 million. Based on WHO thresholds (ICER < GDP per capita ~$1,300), all interventions except lockdowns were considered cost-effective (see Table 2).

Table 2. Cost-effectiveness analysis of major public health interventions.

Intervention	Incremental Cost ($M)	DALYs Averted (Million)	ICER ($/DALY Averted)
Lockdown measures	450	1.2	375
Mass testing	320	2.1	152
Targeted vaccination	280	2.3	122
Contact tracing	110	0.8	138

Risk financing simulations projected a total expected outbreak-related expenditure of $1.2 billion over a 5-year period. Among various financial instruments, a hybrid approach combining a $200 million contingency reserve and a $250 million catastrophe bond was found to reduce unmet funding gaps by 82%, significantly improving fiscal resilience compared to relying solely on ad-hoc budget reallocations (Table 3).

Table 3. Projected funding levels and coverage gaps for selected risk financing mechanisms.

Financing Mechanism	Optimal Funding Level ($M/year)	Coverage Gap Without Mechanism ($M/year)
Contingency reserve fund	180	300
Catastrophe bond	250	400
Contingent credit facility	200	350

Qualitative stakeholder feedback from 22 policymakers, health economists, and public health officials further reinforced the relevance and feasibility of integrating predictive analytics into national preparedness planning. Eighty-six percent of respondents agreed that modeling improves resource prioritization, while 78% emphasized the need for institutionalizing modeling within the federal health ministry. In addition to that, 64% noted limitations due to poor data interoperability and lack of technical expertise, highlighting the importance of investing in digital health infrastructure and workforce development.

DISCUSSION

The results of this study demonstrate that predictive modeling can play a pivotal role in enhancing pandemic preparedness and guiding risk financing strategies in Pakistan. These findings are consistent with global evidence showing the value of data-driven decision-making in public health emergencies. The SEIR compartmental model used in this study successfully simulated disease transmission dynamics, yielding an estimated basic reproduction number (R_0) of 2.8 for SARS-CoV-2, which aligns closely with findings from similar modeling efforts conducted globally, including a multi-country analysis by Liu et al., which reported R_0 values ranging between 2.4 and 3.8 (Liu et al., 2021). The accuracy of forecasting models in predicting dengue outbreaks using Random Forest and LSTM algorithms also supports earlier research from Bangladesh, where machine learning techniques were shown to improve outbreak anticipation by integrating climatic variables (Hasan et al., 2021).

Healthcare capacity modeling revealed significant shortages in basic amenities like hospital beds, ICU units, ventilators, and medical personnel during severe outbreak scenarios. These findings echo those from Nigeria and India, where studies similarly identified critical gaps in surge capacity, particularly in urban centers with high population density (Adedokun et al., 2021; Bora et al., 2021). Unlike high-income countries such as Germany and South Korea, which maintained better healthcare resilience through robust digital infrastructure and pre-existing emergency stockpiles, our results highlight the urgent need for strategic investments in Pakistan's health system to avoid preventable mortalities during future outbreaks (Holmdahl et al., 2021).

In terms of cost-effectiveness, targeted vaccination emerged as the most efficient intervention, with an incremental cost-effectiveness ratio (ICER) well below WHO thresholds for cost-effective interventions (<$1,300 per DALY averted). This aligns with findings from a systematic review conducted in several low- and middle-income countries (LMICs), which concluded that vaccination strategies consistently yield the lowest ICERs compared to other public health measures (Gopalani et al., 2021). However, unlike lockdown measures—which proved relatively inefficient in our model—some studies from India suggested moderate effectiveness of early lockdowns in curbing viral spread, likely due to differences in implementation timing and mobility patterns (Gavi – The Vaccine Alliance, 2021).

Risk financing simulations indicated that a hybrid mechanism combining contingency reserves and catastrophe bonds could reduce unmet funding needs by up to 82%. This supports the framework proposed by Gavi in 2021, which emphasized diversified financial instruments to strengthen fiscal resilience in vulnerable countries (World Bank, 2022). A recent World Bank report similarly recommended integrating predictive analytics into budgeting processes to optimize resource allocation during public health emergencies, reinforcing the relevance of our approach in the Pakistani context (Njuguna et al., 2022).

Stakeholder feedback further validated the utility of predictive modeling in guiding public health decisions. Respondents expressed strong support for incorporating forecasting tools into national planning but highlighted existing challenges such as data fragmentation and limited technical expertise. These concerns resonate with findings from sub-Saharan Africa, where a 2022 survey of public health officials also identified weak data interoperability and workforce readiness as key barriers to implementing predictive tools at scale.

Overall, while contextual factors such as demographic density, economic structure, and healthcare access vary across regions, the methodological rigor and policy relevance of this study make its findings highly transferable to other LMICs facing similar challenges. By building locally adapted models and fostering institutional capacity, Pakistan can transition from reactive crisis management to proactive, data-informed preparedness planning.

Limitations

1. Some datasets were incomplete or outdated due to limited digitization in provincial health systems.
2. Mobility and behavioral data were sparse, limiting the granularity of predictive models.
3. Economic assumptions were subject to uncertainty due to fluctuating inflation and exchange rates.

Strengths

1. Integration of local epidemiological and socioeconomic data into global modeling frameworks.
2. Use of both traditional and machine learning-based forecasting techniques.
3. Policy engagement with key stakeholders to ensure practical applicability.

CONCLUSION

The integration of predictive modeling into public health planning represents a critical step toward strengthening pandemic preparedness and financial resilience in Pakistan. This study demonstrated that epidemiological forecasting models—such as the SEIR framework and machine learning algorithms—are effective tools for anticipating disease outbreaks and guiding proactive resource allocation. The healthcare capacity simulations revealed significant gaps in infrastructure readiness, particularly during severe outbreak scenarios, underscoring the urgent need for targeted investments in hospital beds, ICU units, ventilators, and trained personnel.

Economic evaluation confirmed that targeted vaccination and mass testing campaigns are the most cost-effective interventions, while lockdown measures were found to be relatively inefficient in terms of cost per DALY averted. These findings align with global evidence from other low- and middle-income countries (LMICs), reinforcing the importance of prioritizing high-impact interventions within constrained budgets.

Risk financing simulations further illustrated that a hybrid approach combining contingency reserves and catastrophe bonds could significantly reduce unmet funding needs during health emergencies. Stakeholder feedback validated the relevance of these findings and highlighted the potential for institutionalizing predictive analytics within national health governance frameworks.

In conclusion, adopting a data-driven, model-informed strategy can enable Pakistan to transition from reactive crisis management to proactive, evidence-based preparedness planning. Strategic investments in digital health infrastructure, workforce development, and institutional capacity building will be essential to sustain these gains and ensure long-term resilience against future pandemics.

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