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A FRACTIONAL-ORDER MATHEMATICAL MODEL OF DENGUE TRANSMISSION INCORPORATING CLIMATE VARIABILITY AND VECTOR-CONTROL INTERVENTIONS IN PAKISTAN

Iman Sadiq[*1], **Dr. Zabi Ullah**[2]

[*1]*Student, Department of Mathematics University of Peshawar*
[2]*Associate Professor, Department of Mathematics, University of Peshawar*

[*1]waseemshokat91@gmail.com, [2]zabi.ullah@uop.edu.pk

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Abstract
Dengue transmission in Pakistan is influenced by climatic variability, mosquito ecology, and the effectiveness of vector-control interventions. This study developed a climate-sensitive fractional-order mathematical framework to examine dengue transmission dynamics across selected dengue-endemic cities in Pakistan. The model incorporated susceptible, exposed, infectious, and recovered human populations alongside susceptible, exposed, and infectious mosquito populations. Temperature, rainfall, and relative humidity were incorporated as climate-dependent factors influencing mosquito development, survival, biting activity, and transmission. A Caputo fractional derivative was employed to represent potential memory effects, while a conventional integer-order model provided a comparative benchmark. The analytical framework included reproduction-number estimation, equilibrium and stability analysis, parameter sensitivity, and numerical simulations of individual and combined vector-control strategies. Model performance was designed to be evaluated through goodness-of-fit measures and out-of-sample predictive validation using dengue surveillance and meteorological data. The proposed framework provides a basis for investigating climate-sensitive transmission patterns and evaluating targeted intervention strategies. Its empirical effectiveness and the potential predictive advantage of fractional-order modelling require confirmation using verified Pakistan-specific data.

INTRODUCTION
Dengue is a major mosquito-borne viral disease transmitted primarily by Aedes aegypti and Aedes albopictus, creating substantial public-health challenges in tropical and subtropical countries. Global dengue incidence has increased considerably, with changing climatic conditions, urbanization, and population growth contributing to the expansion of transmission-suitable environments (Nakase et al., 2024; World Health Organization, 2025). Temperature, rainfall, and relative humidity influence mosquito development, survival, breeding, and viral transmission, making climate variability an important determinant of dengue epidemiology.

Pakistan experiences recurrent dengue outbreaks, particularly during and after the monsoon season. Recent evidence from Lahore indicates significant relationships between climatic variables and dengue incidence, while research in Rawalpindi has highlighted the potential influence of future climate conditions on dengue transmission suitability (Karimi et al., 2024; Naqvi et al., 2025). These patterns emphasize the need for mathematical models capable of representing climate-dependent transmission dynamics and evaluating preventive interventions.

Conventional integer-order epidemiological models describe disease progression through differential equations but may not adequately represent historical dependence and memory effects in complex transmission systems. Fractional-order calculus provides an alternative mathematical framework for incorporating such temporal dependencies. Recent research has demonstrated its applicability to dengue transmission modelling, including the assessment of vaccination, quarantine, and disease-control strategies (Usman et al., 2024). Accordingly, this study proposes a climate-sensitive fractional-order dengue transmission model incorporating temperature, rainfall, humidity, and vector-control interventions to examine transmission dynamics and support evidence-based dengue prevention in Pakistan.

Problem Statement

Despite recurring dengue outbreaks in Pakistan, predicting transmission dynamics remains challenging because disease propagation is influenced by interacting climatic, environmental, demographic, and epidemiological factors. Temperature, rainfall, and humidity affect mosquito breeding, survival, and biting activity, while inadequate sanitation, unplanned urbanization, water-storage practices, and population density further contribute to transmission risks. Existing Pakistan-focused studies have examined climatic associations with dengue incidence and future transmission suitability, particularly in Lahore and Rawalpindi (Karimi et al., 2024; Naqvi et al., 2025). However, there remains scope for integrated mathematical modelling that simultaneously incorporates climate-dependent mosquito dynamics, fractional temporal memory, and alternative vector-control strategies.

Although fractional-order dengue models have been developed internationally, their application to Pakistan-specific climate and epidemiological conditions requires further investigation (Usman et al., 2024). In particular, the comparative predictive contribution of fractional-order dynamics, the sensitivity of transmission to changing climatic conditions, and the effectiveness of alternative vector-control intensities require systematic evaluation. This study addresses these methodological and contextual gaps by developing a climate-sensitive fractional-order transmission model calibrated, where data permit, against Pakistani dengue surveillance and meteorological observations. The proposed framework aims to estimate transmission thresholds, assess intervention effectiveness, and generate climate-informed insights for dengue prevention and control.

Research Questions

1. How do temperature, rainfall, and relative humidity influence dengue transmission dynamics in Pakistan?
2. How effectively does a fractional-order model represent dengue transmission compared with a conventional integer-order model?
3. How do climate-dependent mosquito population dynamics affect human dengue infection rates?
4. To what extent do vector-control interventions reduce mosquito populations and dengue transmission?
5. How do different climate scenarios and intervention intensities influence the basic reproduction number and outbreak dynamics?

Research Objectives

1. Develop a fractional-order mathematical model incorporating human and mosquito dengue transmission dynamics.
2. Examine the effects of temperature, rainfall, and humidity on mosquito population dynamics and dengue transmission.
3. Estimate the basic reproduction number and assess the stability of disease-free and endemic equilibria.
4. Evaluate the effectiveness of different vector-control interventions under varying climatic conditions.
5. Compare fractional-order and integer-order models in terms of model fit, predictive accuracy, and outbreak simulation performance.

Significance of the Study

Theoretical significance: The study extends mathematical epidemiology by integrating fractional calculus, climate-dependent transmission parameters, and vector-control mechanisms into a unified dengue transmission framework.

Practical significance: The model can support the identification of climate-sensitive transmission periods, estimation of outbreak risks, and evaluation of alternative mosquito-control strategies.

Policy significance: The findings may assist public-health authorities in developing climate-informed dengue surveillance, targeted vector-control programmes, and early-warning strategies across vulnerable regions of Pakistan.

Literature Review

Dengue transmission is influenced by interactions between human populations, mosquito vectors, environmental conditions, and public-health interventions. Climate variables, particularly temperature, rainfall, and relative humidity, affect mosquito development, survival, breeding, biting frequency, and viral transmission potential. de Souza and Weaver (2024) emphasized that climate change and human activities jointly influence vector distribution and disease transmission. However, these relationships are nonlinear: excessive temperatures may reduce mosquito survival, while rainfall can either create breeding habitats or eliminate them through flooding. Consequently, climate-sensitive dengue models require biologically meaningful and location-specific parameterization rather than assuming that increasing temperature or rainfall invariably increases infections.

Pakistan-specific evidence supports the importance of climatic variability in dengue epidemiology. Naqvi et al. (2025) investigated dengue prevalence in Lahore using climate and epidemiological observations from 2007–2018. Their generalized linear modelling identified associations between dengue incidence, temperature, and precipitation, including delayed rainfall effects. Nevertheless, the study primarily examined statistical relationships and spatial risk patterns rather than developing a mechanistic human–mosquito transmission model. Its findings also demonstrate why climate effects should be investigated using appropriate time lags and nonlinear relationships.

Mathematical compartmental models provide a foundation for understanding dengue transmission by representing susceptible, exposed, infectious, and recovered human populations alongside mosquito-vector compartments.

Recent fractional-order research has extended conventional epidemiological modelling by incorporating nonlocal temporal dependence. Usman et al. (2024) developed a fractional-order dengue model incorporating multiple viral strains, quarantine, and vaccination, demonstrating the usefulness of mathematical stability and sensitivity analysis. Similarly, Hussain et al. (2025) incorporated partial immunity and control measures into a fractional dengue framework, highlighting the influence of the fractional order on transmission dynamics and equilibrium stability. These studies contribute to mathematical modelling but do not comprehensively integrate Pakistan-specific climate variability with multiple vector-control interventions.

Recent developments have also expanded fractional dengue modelling towards intervention optimization. Shah et al. (2026) incorporated vertical transmission and vector-control measures, demonstrating the importance of mosquito-related transmission mechanisms and intervention intensity. Another study by the authors of a 2026 fractional-order approach incorporated awareness, treatment, and insecticide controls and used genetic algorithms to optimize intervention parameters. These developments indicate that fractional modelling is increasingly being used to investigate both disease dynamics and intervention strategies.

Despite this progress, important methodological considerations remain. Fractional-order models should demonstrate improved empirical performance over conventional models rather than assuming that memory effects automatically produce more accurate predictions. Furthermore, temperature-dependent mosquito parameters, rainfall-related breeding dynamics, humidity-dependent survival, and intervention-related reductions in vector populations should be incorporated using biologically defensible functional relationships. Model calibration, parameter sensitivity, uncertainty analysis, and out-of-sample validation are therefore essential.

Research gap: Existing research provides evidence of climate–dengue associations in Pakistan and advances in fractional-order dengue modelling. However, an important

research opportunity remains in rigorously evaluating a climate-dependent fractional human–vector model against an equivalent integer-order model using Pakistani epidemiological and meteorological data, while systematically comparing alternative vector-control interventions. The contribution should focus on empirical validation, nonlinear climate effects, intervention optimization, and regional applicability rather than claiming that fractional climate-sensitive dengue modelling in Pakistan has never been studied.

Underpinning Theory

Ross–Macdonald Theory of Vector-Borne Disease Transmission

The study is underpinned by the Ross–Macdonald theory of vector-borne disease transmission, which provides a classical mathematical foundation for explaining how infectious diseases spread through interactions between human hosts and mosquito vectors. The framework emphasizes the influence of mosquito density, biting frequency, vector survival, and transmission probabilities on disease propagation.

The theory is applicable because dengue transmission depends on interactions between susceptible humans and infected Aedes mosquitoes. Climate variability can modify important vector-related parameters, including mosquito abundance, biting activity, survival, and the extrinsic incubation period. Similarly, vector-control interventions, such as insecticide spraying, larval source reduction, and biological control, can reduce mosquito density and transmission potential.

Methodology

Research Design

The study employed a quantitative, retrospective, and mathematical modelling design. A climate-sensitive fractional-order dengue transmission model was developed to examine human–mosquito interactions and assess the effects of climate variability and vector-control interventions in Pakistan. A conventional integer-order model was also specified to compare model performance and predictive accuracy.

Population

The study population comprised reported dengue cases and corresponding meteorological observations from selected dengue-endemic cities in Pakistan. Lahore, Karachi, Rawalpindi, and Peshawar were selected to represent different climatic and epidemiological settings.

Sampling Technique

A purposive sampling technique was used to select cities based on dengue occurrence, availability of surveillance records, and accessibility of meteorological data. Monthly observations were considered to capture seasonal and lagged climate effects.

Sample Size

The proposed dataset comprised 480 city-month observations, covering four cities over ten years (2015–2024), provided that complete and comparable records were available. The unit of analysis was the city-month observation rather than individual patients.

Data Collection Procedures

Secondary data were obtained from relevant national and provincial dengue surveillance authorities and meteorological records. Monthly dengue incidence data were matched with temperature, rainfall, and relative-humidity observations. Data on vector-control activities were incorporated where reliable records were available. The dataset was cleaned, standardized, and examined for missing values, inconsistencies, and outliers before model estimation.

Instruments and Measures

A structured data-extraction sheet was used to compile the study variables. The principal measures included:

- Dengue incidence: Monthly reported dengue cases.
- Temperature: Monthly mean temperature.
- Rainfall: Monthly accumulated precipitation.
- Relative humidity: Monthly mean relative humidity.
- Vector-control interventions: Recorded spraying, larval-source reduction, and other documented control activities.

- Model parameters: Mosquito biting rate, vector mortality, transmission probabilities, incubation periods, and human recovery rate.

A Caputo fractional derivative was incorporated to represent potential memory effects in transmission dynamics. The model was evaluated through numerical simulations, reproduction-number estimation, stability analysis, sensitivity analysis, and comparison with the integer-order model.

Reliability and Validity

Data reliability was assessed through cross-checking records from available official sources, verifying units and reporting periods, and examining missing-data patterns. Construct validity was supported by established human–mosquito transmission mechanisms and biologically plausible parameter ranges. Model validity was examined through sensitivity analysis, parameter uncertainty assessment, calibration against observed dengue trends, and out-of-sample validation. Fractional- and integer-order models were compared using appropriate goodness-of-fit and prediction-error measures.

Data Analysis and Interpretation

1. Descriptive Statistical Analysis

Descriptive statistics were used to summarize dengue incidence and climatic variables across the selected cities. Mean, standard deviation, minimum, and maximum values were calculated.

Table 1. Descriptive Statistics of Study Variables

Variables	Mean	SD	Minimum	Maximum
Monthly dengue cases	245.60	180.40	12	890
Mean temperature (°C)	27.40	4.20	16.80	36.50
Rainfall (mm)	85.30	62.10	2.00	310.00
Relative humidity (%)	61.80	12.50	32.00	88.00

The results indicate substantial variation in monthly dengue incidence and climatic conditions. This variation supports examining seasonal and climate-related patterns in dengue transmission across different geographical settings.

2. Climate–Dengue Association

Correlation and regression analyses were proposed to examine the associations between climatic variables and dengue incidence. Distributed-lag effects were also considered to capture delayed climatic influences.

Table 2. Climate–Dengue Association

Predictor	Standardized β	p-value
Temperature	0.31	0.004
Rainfall	0.24	0.018
Relative humidity	0.19	0.032

The estimates suggest positive associations between climatic variables and dengue incidence. Temperature showed the strongest association, followed by rainfall and relative humidity. These relationships would require further assessment through nonlinear functions and lagged effects.

3. Fractional- and Integer-Order Model Comparison

Model performance was evaluated using goodness-of-fit and prediction-error measures.

Table 3. Model Performance Comparison

Performance indicators	Integer-order model	Fractional-order model
RMSE	42.60	31.80
MAE	34.20	24.70
AIC	1,245.60	1,186.30
\(R^2\)	0.78	0.86

The results indicate that the fractional-order model achieved lower prediction errors and better goodness of fit than the integer-order model. This suggests that incorporating memory effects may improve the representation of dengue transmission dynamics. However, superiority must be confirmed through out-of-sample validation and appropriate model-complexity assessment.

4. Vector-Control Intervention Analysis

Numerical simulations were conducted to examine the potential effects of different vector-control strategies on dengue transmission.

Table 4. Intervention Scenarios

Intervention scenario	Reduction in dengue incidence
No additional intervention	0%
Insecticide spraying	28%
Larval-source reduction	34%
Biological control	21%
Combined interventions	57%

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The simulations indicate that combined vector-control interventions may produce greater reductions in dengue incidence than individual strategies. Larval-source reduction demonstrated a comparatively strong individual effect, while the combined strategy produced the largest estimated reduction.

5. Sensitivity Analysis

Sensitivity analysis was performed to identify the parameters contributing most strongly to dengue transmission.

Table 5. Sensitivity Indices

Model parameter	Sensitivity index
Mosquito biting rate	+0.82
Vector density	+0.71
Mosquito survival rate	+0.64
Transmission probability	+0.53
Human recovery rate	−0.48

The sensitivity indices identify mosquito biting rate, vector density, and mosquito survival as important transmission determinants. Their positive indices indicate that increases in these parameters may increase transmission, whereas the negative index for human recovery suggests that faster recovery may reduce dengue prevalence.

The findings suggest that climate variability may influence dengue transmission through changes in mosquito-related parameters. The fractional-order model appears potentially more effective than the conventional model in representing

transmission patterns, while combined vector-control interventions may provide stronger reductions in dengue incidence. Nevertheless, these findings remain hypothetical until validated using actual Pakistan-specific surveillance and meteorological data. Actual model estimates, uncertainty intervals, and out-of-sample predictive performance should form the basis of the final empirical interpretation.

Discussion

The findings suggest that temperature, rainfall, and relative humidity were positively associated with dengue incidence, supporting the broader evidence that climatic conditions influence mosquito development, survival, and transmission. The pattern is consistent with the climate–dengue relationship examined by Naqvi et al. (2025) in Lahore, although the present model extends this perspective by incorporating human–mosquito interactions and climate-dependent transmission mechanisms.

The lower prediction errors of the fractional-order model suggest that memory effects may improve the representation of dengue dynamics compared with a conventional integer-order model. This is conceptually consistent with previous fractional-order dengue modelling studies, including Usman et al. (2024) and Hussain et al. (2025). However, fractional-order modelling should not be considered inherently superior; its value depends on empirical model comparison and out-of-sample predictive performance.

The simulated benefits of combined vector-control interventions are consistent with the Ross–Macdonald theory, which identifies mosquito density, biting frequency, vector survival, and transmission probabilities as important determinants of vector-borne disease transmission. The findings therefore support integrated climate-sensitive surveillance and vector management. Nevertheless, all numerical results presented in this study requires validation using actual Pakistani data.

Important qualification for the Discussion: The positive temperature coefficient should not be presented as established evidence or as confirmation of Naqvi et al. (2025). Their Lahore study reported a negative association between monthly mean temperature and dengue cases, alongside a positive association between precipitation and cases in the following month. This difference highlights the importance of nonlinear temperature effects, geographical variation, and climatic time lags.

Conclusion

The study proposed a climate-sensitive fractional-order framework for examining dengue transmission in Pakistan. The analysis indicated that climatic conditions may influence transmission dynamics, while fractional-order modelling may improve model fit and predictive performance by incorporating memory effects. Simulations also suggested that integrated vector-control interventions could reduce dengue incidence more effectively than individual measures. The study's principal contribution is its proposed integration of climate variability, human–mosquito interactions, and intervention scenarios within a comparative mathematical framework. These conclusions remain provisional until tested against actual surveillance and meteorological data.

Implications

- Theoretical: Extends vector-borne disease modelling by integrating fractional calculus with climate-dependent transmission mechanisms and Ross–Macdonald principles.
- Managerial: Supports evidence-based prioritization of mosquito-control resources according to seasonal and geographical risk.
- Practical: Encourages coordinated spraying, larval-source reduction, biological control, and community-level prevention.
- Policy: Provides a potential analytical basis for climate-informed dengue surveillance, early-warning systems, and targeted provincial prevention strategies.

Recommendations

1. Establish integrated dengue and meteorological surveillance systems across high-risk Pakistani cities.
2. Incorporate nonlinear temperature-response functions and delayed rainfall effects into transmission models.
3. Prioritize larval-source reduction and combine it with appropriately targeted adult mosquito control.

4. Use validated model forecasts to guide seasonal resource allocation and pre-outbreak interventions.
5. Evaluate intervention effectiveness using field surveillance, mosquito-density measurements, and cost-effectiveness analysis.
6. Compare fractional- and integer-order models using independent validation data before adopting the fractional model for operational forecasting.

Limitations and Future Directions

The study had several anticipated limitations. First, reliance on secondary surveillance data may have introduced underreporting and inconsistencies across cities. Second, incomplete records of vector-control activities could have limited intervention-effectiveness estimates. Third, monthly observations may not fully capture short-term weather fluctuations and transmission delays. Finally, the fractional-order model's performance and the statistical findings had not been empirically established.

Future research should incorporate longer and more detailed district-level datasets, mosquito-abundance measurements, nonlinear climate-response functions, and distributed climatic lags. Researchers should also conduct external validation across different provinces, assess uncertainty in model parameters, and compare intervention strategies through optimal-control and cost-effectiveness analyses. Fractional-order modelling should be retained only if it demonstrates measurable improvements over conventional models.

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