

Modeling PM2.5: Temperature Interactions Using Predator-Prey Dynamics

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ABSTRACT

This study introduces a novel application of the predator-prey concept to model and forecast daily PM2.5 concentrations, with PM2.5 treated as the prey and temperature as the predator. This formulation reflects the commonly observed inverse relationship between pollution levels and temperature in urban atmospheric environments. A dynamic equation was constructed to describe the rate of change in PM2.5, incorporating both intrinsic growth and the suppressive effect of temperature. Regular environmental cycles are also incorporated into the model structure. Parameters were estimated using daily observational data collected over a three-month period. The model successfully captures short-term variation and broader seasonal trends in PM2.5, despite relying on temperature as the sole external variable. This approach provides a simplified yet interpretable framework that explains how pollution levels respond to environmental drivers over time. It represents a conceptual shift from purely statistical models by offering an ecological perspective on air quality dynamics. Predictive validation yielded RMSE values of 15.7036 for PM2.5 and 0.9425 for temperature, demonstrating strong agreement with observed data. This is the first study to adapt predator-prey principles to describe and predict the interaction between temperature and PM2.5 on a daily time scale.

HIGHLIGHTS

A predator-prey model analyzes interactions between PM2.5 and temperature. PM2.5 is modeled as prey and temperature as predator with seasonal and daily effects. This approach supports improved air quality forecasting and pollution management.

1. INTRODUCTION

Over the past decade, particulate matter with a diameter of 2.5 micrometers or less (PM2.5) has emerged a critical global environmental and public health concern. Due to its extremely small size, PM2.5 can penetrate deep into the respiratory system and bloodstream, leading to serious health consequences such as cardiovascular diseases, respiratory disorders, and lung cancer. This issue is particularly severe in rapidly in urban areas, including Bangkok, Thailand. High traffic density, combustion, and industrial activities contribute to elevated PM2.5 concentrations. Recent studies, further confirm that urban air pollution poses significant health risks for Bangkok's population. Findings indicate a clear association between ambient PM2.5 exposure and increased all-cause mortality, with particularly strong links to stroke and chronic

obstructive pulmonary disease (COPD). Importantly, these health effects occur even at relatively low exposure levels, emphasizing that PM2.5 remains a persistent threat. This underscores the urgent need for effective and stringent pollution control measures to safeguard public health in major cities like Bangkok. (Phosri et al., 2018; Fold et al., 2020).

Studying the impacts of meteorological variables in Bangkok during the winter season offers distinct advantages. During the dry winter months of November to January, PM2.5 levels in Bangkok often peak, as precipitation is typically negligible. This period was selected to examine the influence of meteorological variables on PM2.5 without considering the effects of precipitation. For instance, analysis of PM2.5 data in Bangkok during November-December 2016 to 2018 revealed strong correlations

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with meteorological factors, including wind speed, relative humidity, and temperature. Understanding these complex relationships is essential for developing effective air quality management strategies (Ketjulan et al., 2023). This observation aligns with the findings of Sirithian and Thanatrakolsri (2022), who reported significant correlations between meteorological variables, particularly temperature, relative humidity, and wind speed and PM_{2.5} concentrations in northern Thailand during the dry haze season. Their study highlighted that during periods of minimal rainfall, these meteorological factors serve as the primary drivers influencing particulate matter level. Applying similar reasoning to Bangkok, which experiences similarly dry atmospheric conditions during the winter months, reinforces the importance of focusing on these variables when developing accurate daily forecasting models for PM_{2.5} concentrations (Ruttanawongchai et al., 2018).

Most studies primarily use statistical methods, such as correlation and regression analysis, to examine the relationship between PM_{2.5} and meteorological variables, rather than focusing on daily forecasting (Lu and Ma, 2020). This research proposes a novel approach by applying the predator-prey model, a mathematical framework originally developed to describe ecological interactions between species, such as the influence of the wolf populations on rabbit populations, which have the predator-prey relationship. The model uses differential equations to capture the dynamic interplay of growth and decline rates. The hypothesis of this study is that the predator-prey model can effectively capture the complex relationships between PM_{2.5} concentrations and temperature in Bangkok during the winter season (November to January). This approach is expected to facilitate the development of a highly accurate daily PM_{2.5} forecasting model.

Temperature has a complex, dual-phase effect on particulate matter dynamics. Higher temperatures increase molecular kinetic energy and promote vertical mixing processes, facilitating pollutant dispersion, whereas lower temperatures increase atmospheric density and limit convective mixing, promoting particulate accumulation in lower atmospheric layers (Yang et al., 2017). Temperature exerts a notable influence on PM_{2.5} concentration, with lower temperatures often correlating with higher PM_{2.5} levels. Cold conditions, particularly during in winter, contribute to the formation of temperature

inversion layers that trap pollutants near the surface, limiting vertical mixing, promoting particulate accumulation. Additionally, the use of coal for heating during colder months further exacerbates PM_{2.5} pollution. When combined with low wind speeds and high humidity, these conditions create an environment in which air pollutants are more likely to concentrate in the lower atmosphere (Yang et al., 2023).

Temperature is considered the “predator” within the PM_{2.5}-temperature dynamic system due to its demonstrably inverse relationship with PM_{2.5} concentrations. Elevated temperatures promote atmospheric instability and vertical dispersion of pollutants, thereby reducing particle accumulation an effect to how a predator regulates the growth of a prey population. Moreover, the observed interactions between PM_{2.5} and thermal profiles, such as the urban heat island effect, further support the suitability of this ecological modeling framework. This selection aligns with extensive research identifying temperature as a predominant meteorological factor influencing ambient PM_{2.5} levels. This approach provides a robust basis for analyzing the complex interplay between atmospheric conditions and particulate matter dynamics (Winalai et al., 2022). The proposed predator-prey model represents a novel approach to analyzing the interaction between PM_{2.5} concentrations and temperature. While traditional aerosol dynamics models like Chemical Transport Models, primarily focus on pollutant dispersion and chemical transformation, our predator-prey model introduces an ecological perspective by treating temperature as a “predator” and PM_{2.5} as its “prey”. This dynamic framework captures seasonal feedback loops and interactions between environmental factors, offering a fresh framework for understanding air pollution patterns over time (Lai et al., 2024).

The findings are expected to improve understanding of PM_{2.5} dynamics in Bangkok, a city facing persistent air pollution challenges. The predator-prey approach provides a novel tool for air quality forecasting. By introducing an ecological modeling perspective, this research offers a unique contribution to air quality management and advances the understanding of the complex interplay between PM_{2.5} and temperature. Utilizing a predator-prey model to develop a predictive framework for PM_{2.5} and temperature enables effective monitoring of air quality impacts and helps identify of critical factors for controlling PM_{2.5} concentrations.

2. METHODOLOGY

2.1 PM2.5-temperature interaction model

Predator-prey model

The predator-prey model is a mathematical framework that describe the dynamics interaction between two populations: predators and prey. It illustrates how the population of prey increases when resources are abundant and declines in the presence predators, while the predator population grows when prey is plentiful and declines as prey becomes scarce. This interaction typically leads to oscillating population sizes for both groups, with predators and prey populations rising and falling in a cyclical pattern. The model provides insights into natural population control and the balance between species in ecosystems (Murray, 2002).

We use PM2.5 and temperature data obtained from the Thailand Pollution Control Department and Weather Underground, focusing on the winter season during November and December 2024 to January 2025. The study specifically considered the area around Don Mueang International Airport, located at 13.92°N, 100.6°E in Bangkok, Thailand. The stability and accuracy of the model were further evaluated through the eigenvalues analysis, and the Routh-Hurwitz criterion was applied to assess system stability, ensuring the robustness of the proposed model.

The present investigation adapts and modifies the classical predator-prey framework, originally formulated by Lotka and Volterra, to explore dynamic interactions between PM2.5 concentrations and meteorological parameters (temperature). Within this conceptual framework, PM2.5 is treated as the “prey” species, while temperature acts as predatory forces exerting regulatory influence upon particulate matter concentrations. In this model, we adopted a sigmoid function to represent the temperature’s effect on PM2.5, which qualitatively mirrors the Holling Type III functional response (Holling, 1959a; Holling, 1959b). This approach captures the critical-point and saturating nature of environmental interactions, where temperature only significantly reduces PM2.5 after concentrations exceed a certain level. Such a response is more realistic than linear forms, and aligns with ecological and atmospheric dynamics (Jianhua and Susumu, 2015). We will define the PM2.5 and temperature model as;

Prey equation (PM2.5),

$$\frac{dP}{dt} = \alpha P \left(1 - \frac{P}{K}\right) - \beta PT \left(\frac{1}{1 + e^{-k(P-P_0)}}\right)$$

$$-\delta PT^2 + \xi_1 \sin(\omega_1 t + \phi_1) + \xi_2 \cos(\omega_2 t + \phi_2) \quad (1)$$

Predator equation (Temperature),

$$\frac{dT}{dt} = -\gamma PT + \mu \left(\frac{1}{1 + e^{-k(P-P_0)}}\right) \quad (2)$$

We set $P_0=85$ for the transitions in thermal effect in the model. Most model parameters (listed in Table 1) were estimated using nonlinear regression on the 92-day PM2.5-temperature dataset, while all remaining parameters were determined through optimization using real observational data. Data preprocessing included handling any missing values and normalizing the observations prior to model fitting. These steps ensure that the model reproduces both short-term fluctuations and seasonal patterns in the observed data.

The methodology is designed to produce robust, and replicable results, suitable for air quality forecasting and environmental policy development.

2.2 Stability of the model

To ensure the robustness and reliability of the proposed predator-prey model, we conducted a stability analysis to verify the equilibrium points under varying conditions. This analysis is essential to confirm that the model behaves consistently and provides meaningful predictions over time. Specifically, we use Eigenvalues and the Routh-Hurwitz Criterion to assess the model stability, ensuring that the equilibrium points remain stable and the system responds predictably to parameter changes.

Our focus is on the equilibrium point where both PM2.5 and temperature exist at non-zero values, reflecting their observed presence in real-world data. Based on calculations, we get the equilibrium point for the system of interest.

$$(P^*, T^*) = (120.14, 37.32) \quad (3)$$

Jacobian matrix at equilibrium point,

$$J(P^*, T^*) = \begin{bmatrix} -0.0153 & 0.1705 \\ -0.0033 & -0.0106 \end{bmatrix} \quad (4)$$

We get the eigenvalues,

$$\lambda_1 = -0.0129 + 0.0236i \quad (5)$$

$$\lambda_2 = -0.0129 - 0.0236i \quad (6)$$

Table 1. Meaning of parameters in the model

Symbol	Meaning	Values of the parameters
P	PM2.5 concentration	
T	Temperature	
t	Time	
K	Carrying capacity of PM2.5	172
α	Growth rate of PM2.5	0.015
β	Predation rate	0.00191764
k	The slope of the sigmoid function	0.5
δ	PM dispersion rate	-0.0000447
ξ_1	Seasonal forcing	5.9800
ξ_2	Daily forcing	5.5955
ω_1	Frequency of seasonal	0.0100
ω_2	Frequency of daily	6.2458
ϕ_1	Phase shift	2.1401
ϕ_2	Phase shift	3.7893
γ	Temperature decrease rate by PM2.5	0.0000881
μ	Temperature increase by PM2.5 effect	0.3949

All eigenvalues have negative real parts, the system is stable (Basak and Lee, 2008).

Routh-Hurwitz criterion test, from the eigenvalues (5) and (6) we get the characteristic equation,

$$s^2 + 0.259s + 0.000723 = 0 \quad (7)$$

Which,

$$a_2 = 1, a_1 = 0.259, a_0 = 0.00072$$

There are no sign changes, which mean the system is stable (Medhi et al., 2024).

3. RESULTS AND DISCUSSION

This study developed a nonlinear predator-prey model to investigate the interaction between PM2.5 concentrations and temperature in Bangkok during the winter season. The system comprises two coupled differential equations, with PM2.5 modeled as the “prey” and temperature as the “predators”, representing a novel framework for urban air quality modeling. This analogy provides a dynamic systems perspective, capturing not only correlation but also causality and regulatory mechanisms, in contrast to conventional statistical or machine learning approaches. Key mechanisms, such as logistic growth, threshold responses, and periodic external forcing, were incorporated to reflect seasonal and diurnal dynamics. While previous studies often rely on

regression analysis to analyze air pollution, the predator-prey framework naturally integrates nonlinear feedback and stability analysis, making it more suitable for modeling complex environmental systems with the ability to capture feedback loops and saturation effects (Murray, 2002).

Model calibration and equilibrium analysis were conducted, using daily observations from November 2024 to January 2025 (92 days total). Model parameters were either derived empirically or estimated through regression fitting as shown in Table 1. The stability of the model was validated using eigenvalue analysis and the Routh-Hurwitz criterion, confirming the presence of a locally stable equilibrium under the observed conditions (Themairi and Alqudah, 2020).

To evaluate model performance, the predicted values of PM2.5 and temperature were compared with actual observations. Figure 1 illustrates the comparison between the observed PM2.5 concentrations and the values predicted generated by the proposed predator-prey model, while. Figure 2 presents the comparison between the observed temperature and model-predicted temperature during the study period and Figure 3 shows both variables together. The root mean square error (RMSE) for PM2.5 was 15.7036 and 0.9425 for temperature. These values demonstrate strong agreement, especially given the inherent variability and nonlinearity of urban atmospheric systems.

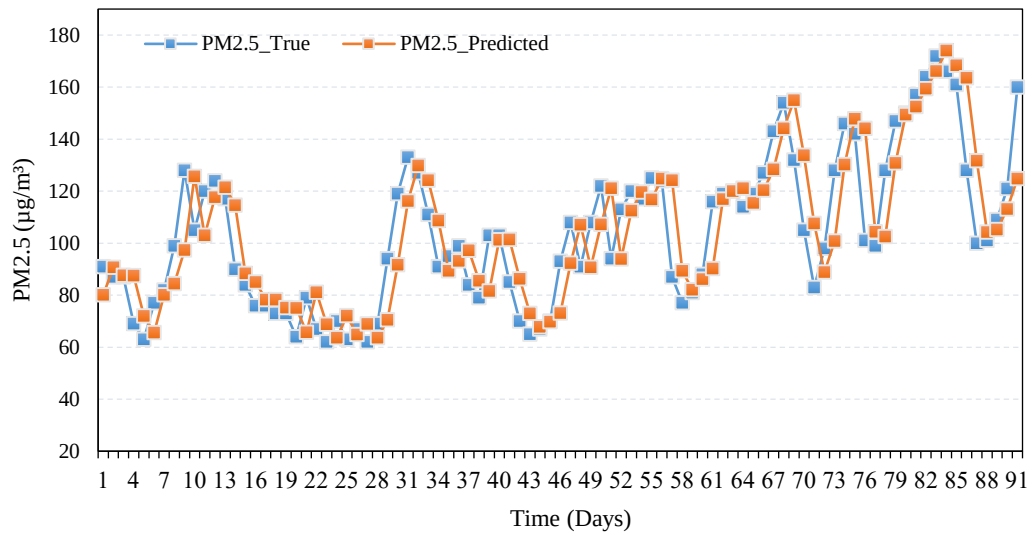


Figure 1. PM2.5 true vs predicted

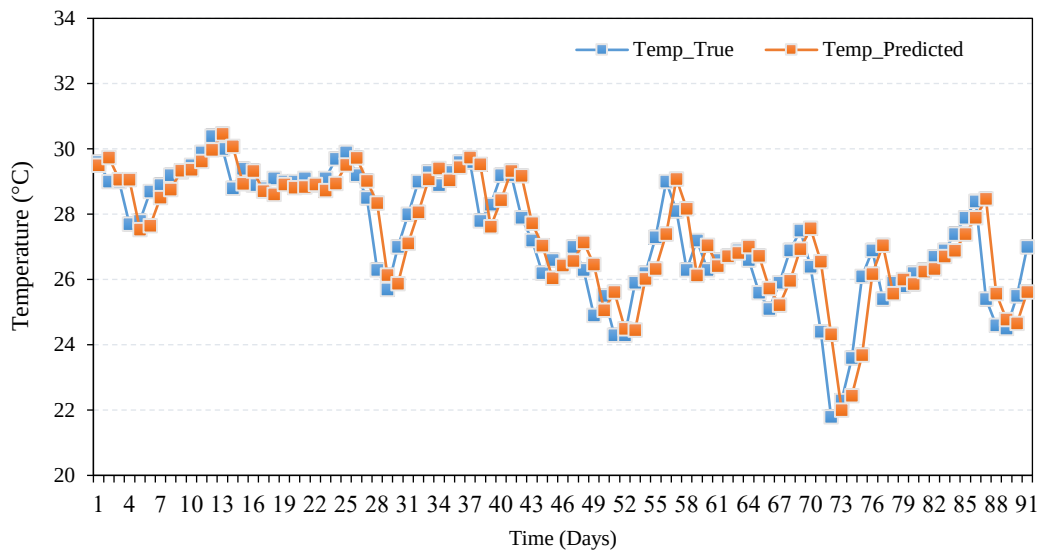


Figure 2. Temperature true vs predicted

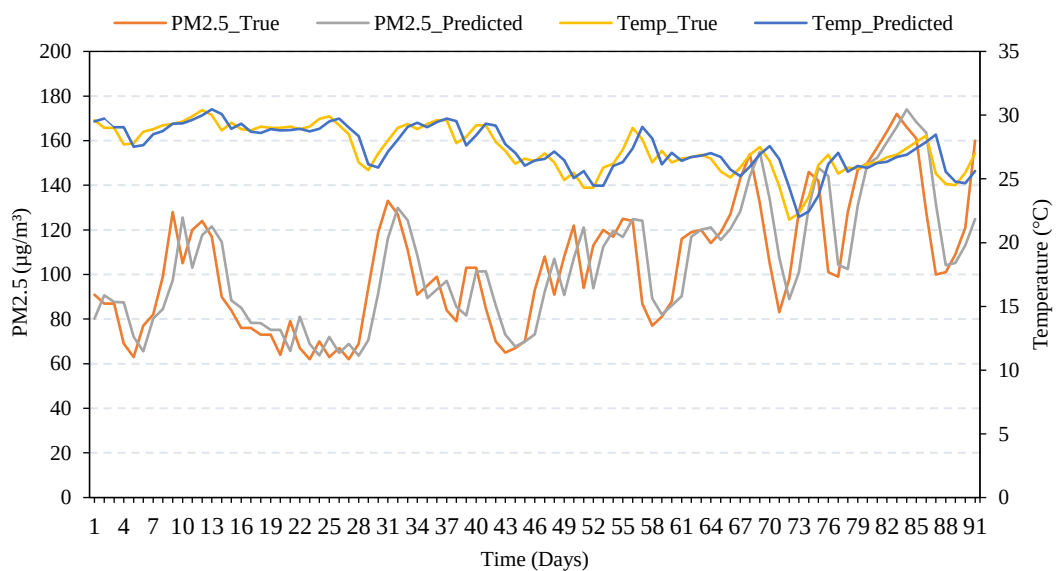


Figure 3. PM2.5 and Temperature true vs predicted

Interpretation and Implications: The model not only confirms the known inverse relationship between temperature and PM_{2.5} but also provides a mechanistic explanation for threshold effects: temperature effectively reduces PM_{2.5} only when pollution levels exceed a critical point, consistent with urban temperature inversions. This insight goes beyond empirical findings by identifying causal thresholds, which can help inform more effective timing of policy interventions. Additionally, the inclusion of periodic forcing terms such as daily traffic cycles, enhances the model's accuracy, allowing it to capture recurring PM_{2.5} peaks driven by daily traffic patterns and seasonal variations in solar radiation.

The predator-prey analogy treating (temperature as the “predator”, PM_{2.5} as “prey”) was adopted to represent the dynamic interaction between temperature and PM_{2.5}. In urban environments, the boundary-layer dynamics play a crucial role in regulating the PM_{2.5} dispersion, with temperature influencing atmospheric stability and turbulence. Additionally, diurnal temperature variation affects the daily cycle of PM_{2.5} concentrations, as higher day time temperatures enhancing dispersion and lower concentrations, while nighttime inversions trap pollutants near the surface (Miao et al., 2019). This mechanistic understanding of physical processes supports the predator-prey analogy and strengthens the ecological basis of the model.

Compared to conventional empirical or data-driven models, the predator-prey approach offers greater theoretical depth, by enabling formal analysis of system stability and potential regime shifts. For example, the identification of an equilibrium state allows for simulation of long-term outcomes under various policy scenarios, which is often not possible with purely statistical models.

Despite its simplified two-variable structure, the model effectively represents urban air pollution. It also offers a flexible foundation for future extensions, such as incorporating additional meteorological variables to enhance predictive performance. In future work, extending the model to include multiple “prey” or “predator” species (e.g., different pollutants or atmospheric drivers) could further broaden its applicability and realism.

Practical Implications: The developed model offers a practical tool for daily air quality forecasting, enabling relevant authorities to issue more accurate public health advisories and pollution warnings. This study focuses on modeling PM_{2.5} concentrations

during the winter season, when pollution levels are typically highest. As a result, the findings and policy recommendations are most applicable to the winter months, and the model's applicability to other seasons remains limited. By predicting PM_{2.5} peaks based on temperature forecasts, proactive measures such as traffic control or industrial emission reductions can be implemented in advance to mitigate severe pollution episodes. Furthermore, the identification of a stable equilibrium state provides insights for long-term environmental policy planning, suggesting that managing key drivers like urban heat could help maintain air quality within acceptable limits. This model can be integrated into early warning systems, it can support targeted interventions, such as restricting high-emission vehicles during predicted high-pollution periods. Additionally, the conceptual framework of temperature as a regulatory “predator” offers an intuitive way to communicate complex atmospheric dynamics to the public, fostering greater awareness and adherence to health guidelines during critical periods. By integrating this model into early warning systems to support targeted interventions, such as limiting high-emission vehicles during forecasted high-pollution events. Moreover, framing temperature as a regulatory “predator” provides an intuitive and accessible way to communicate complex atmospheric dynamics to both policymakers and the general public, potentially increasing awareness and compliance with health guidelines during critical periods (Rizwan et al., 2008).

While the model demonstrated good accuracy with RMSE values during the three-month validation period, we acknowledge that the short duration limits its robustness. Future work will focus on to expand the validation period by incorporating data from several years of winter seasons, which is when PM_{2.5} levels in Thailand are typically the highest. Additionally, out-of-sample validation will be conducted using data from other regions to test the model's generalizability and long-term applicability across different locations and environmental conditions.

4. CONCLUSION

This study presents a nonlinear model that captures the dynamic interaction between PM_{2.5} concentration and ambient temperature, introducing a novel concept through the predator-prey model framework. By incorporating logistic growth, a threshold response, and periodic external forcing, the model captures key behaviors observed in urban

atmospheric systems-particularly the delayed suppressive effect of temperature on PM_{2.5} and the recurrence of pollution peaks linked to seasonal and daily cycles.

The model was calibrated with real-world data spanning 92 days across winter months, and equilibrium analysis confirmed local stability with realistic PM and temperature levels. Predictive validation yielded good agreement between simulated and observed values, indicating that the model can capture short-term fluctuations as well as broader seasonal patterns with reasonable accuracy.

Beyond its predictive capability, the model contributes conceptually by reinterpreting temperature as a regulatory agent-analogous to a predator in ecological systems-acting nonlinearly upon pollution accumulation. This reinterpretation offers a valuable lens for understanding how environmental variables interact not merely through correlation, but through dynamic control mechanisms involving thresholds and feedbacks. Such an approach bridges the gap between empirical atmospheric analysis and mechanistic ecological modeling, enabling the use of well-established mathematical tools such as equilibrium analysis, Jacobian stability, and phase-space behavior.

The identification of a stable equilibrium with interpretable values for both PM_{2.5} and temperature suggests that the system, under typical winter conditions, tends toward a quasi-stable state unless perturbed by strong external forcing. This reinforces the practical relevance of the model in providing not just forecasts, but also insights into the stability and major changes in urban air quality systems.

Future applications may include integrating this model with meteorological forecast inputs, or coupling it with emission inventories for localized policy testing. Furthermore, the structure lends itself to extensions, such as adding humidity and wind variables or implementing spatial diffusion terms to account for inter-area interaction. In sum, the proposed framework offers a compact yet expressive tool for both analysis and predicting complex urban pollution dynamics.

This model offers a new ecological perspective that can stimulate interdisciplinary research in urban environmental management. It underscores the potential of leveraging well-established biological frameworks to understand and predict complex environmental phenomena, ultimately contributing to more resilient and sustainable cities amid escalating air pollution challenges.

AUTHOR CONTRIBUTIONS

Conceptualization, W.S., I.N., and S.R.; Methodology, W.S.; Validation, W.S., I.N., and S.R.; Model Analysis, W.S. and I.N.; Writing-Original Draft Preparation, W.S.; Writing-Review and Editing, I.N. and S.R.; Supervision, I.N. and S.R.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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