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ICCRAIDS 2026

International Conference on Current Research in Artificial Intelligence and Data Science

Program Book

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2026

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PROCEEDINGS

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1. WELCOME MESSAGE

Praise be to God for His blessings and guidance. On behalf of Universitas AMIKOM Purwokerto, I am honored to welcome all distinguished speakers, researchers, authors, and participants to the International Conference on Current Research in Artificial Intelligence and Data Science (ICCRAIDS) 2026.

This conference serves as an important platform for academics, researchers, professionals, and students from around the world to exchange ideas and share recent advances in artificial intelligence, data science, and related fields. As these technologies continue to transform many aspects of society, collaboration and knowledge sharing are increasingly essential to addressing complex challenges and creating innovative solutions for the future.

ICCRAIDS 2026 aims to promote high-quality research and foster interdisciplinary collaboration among scholars and practitioners. Through keynote lectures, technical paper presentations, and academic discussions, we hope the conference contributes to cutting-edge research and encourages meaningful dialogue that advances artificial intelligence and data science.

Universitas AMIKOM Purwokerto remains committed to supporting research, innovation, and academic collaboration that strengthen the role of higher education in technological development and digital transformation. We believe events such as ICCRAIDS not only advance scientific knowledge but also build strong international networks for future collaboration.

I would like to express my sincere appreciation to the organizing committee, technical program committee, reviewers, partners, and sponsors for their time and expertise in making this conference possible. I also extend my gratitude to all authors and participants for sharing their valuable research and insights.

I wish all participants a productive and inspiring conference, and I hope ICCRAIDS 2026 provides valuable experiences, fruitful discussions, and new opportunities for collaboration.

Thank you.

Assoc. Prof. Dr. Berlilana, M.Kom., M.Si.
Rector
Universitas AMIKOM Purwokerto

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2. MESSAGE FROM THE GENERAL CHAIR

On behalf of the organizing committee, it is my great pleasure to welcome you to the International Conference on Current Research in Artificial Intelligence and Data Science (ICCRAIDS) 2026. We are delighted to bring together researchers, academics, practitioners, and students from various institutions and countries to share their latest research and ideas in the rapidly evolving fields of artificial intelligence and data science.

Artificial intelligence and data-driven technologies have become central to innovation across many sectors, including healthcare, education, industry, finance, and public services. As these technologies continue to advance, it is increasingly important to create opportunities for researchers and professionals to exchange knowledge, discuss emerging challenges, and collaborate on future solutions. ICCRAIDS is designed to serve as a platform that facilitates such meaningful interaction and collaboration.

This conference features keynote talks from distinguished speakers, technical paper presentations, and academic discussions covering a wide range of topics related to artificial intelligence, machine learning, data analytics, and intelligent systems. We hope that the discussions and presentations during this conference will stimulate new ideas and encourage further research and collaboration among participants.

I would like to express my sincere appreciation to the Program Committee, reviewers, organizing committee members, sponsors, and partners for their dedication and hard work in making this conference possible. Their efforts in reviewing submissions and organizing the event have ensured the quality and success of ICCRAIDS 2026.

Finally, I would like to thank all authors and participants for their valuable contributions and for being part of this conference. I wish you a productive and inspiring conference experience, and I hope that ICCRAIDS 2026 will provide an excellent opportunity for knowledge exchange and future collaboration.

Thank you.

Prof. Dr. Taqwa Hariguna, S.T., M.Kom.

General Chair

3. MESSAGE FROM THE PROGRAM CHAIR

It is my great pleasure to welcome you to the International Conference on Current Research in Artificial Intelligence and Data Science (ICCRAIDS) 2026. As the Program Chair, I am honored to present a program that highlights current research developments and innovative applications in artificial intelligence and data science. The goal of ICCRAIDS 2026 is to provide a forum where researchers, scholars, and practitioners can present and discuss their latest research findings. The conference received submissions from various institutions and research communities, reflecting the growing interest and rapid progress in AI and data science. Each submitted paper underwent a peer-review process conducted by members of the Technical Program Committee and expert reviewers to ensure the quality and relevance of the accepted contributions.

The technical program includes keynote speeches by distinguished experts as well as parallel sessions featuring selected research papers. These sessions cover a variety of topics, including machine learning, data analytics, intelligent systems, and other emerging areas related to artificial intelligence and data science. We believe that the program will offer valuable insights and inspire further research and collaboration among participants.

I would like to extend my sincere gratitude to the members of the Technical Program Committee and reviewers for their time, expertise, and dedication in evaluating the submissions. I also thank the organizing committee and all contributors who have worked diligently to prepare this conference program.

We hope that ICCRAIDS 2026 will provide a stimulating academic environment for sharing knowledge, discussing ideas, and building new collaborations. I wish you an engaging and rewarding conference experience.

Thank you.

Prof. Dr. Eng. Ir. Imam Tahyudin, M.M.

Program Chair

4. SPECIAL MESSAGE

It is my great pleasure to extend warm greetings to the organizers, distinguished speakers, and participants of the International Conference on Current Research in Artificial Intelligence and Data Science (ICCRAIDS) 2026.

The rapid advancement of artificial intelligence and data science is reshaping many aspects of modern life, offering new opportunities to address complex societal challenges while driving innovation across various sectors. Conferences such as ICCRAIDS play an important role in bringing together researchers, academics, practitioners, and industry professionals from different parts of the world to exchange ideas, share knowledge, and foster meaningful collaboration that advances technology and research.

I am particularly pleased to see this international academic gathering associated with Banyumas and the city of Purwokerto. Banyumas Regency, located in the southwestern part of Central Java, is known for its strong educational environment and vibrant academic community. Supported by several universities and research institutions, the region continues to grow as a center for learning, research, and innovation that contributes to regional and national development.

We welcome initiatives that promote knowledge exchange and international collaboration, as they help strengthen the role of education and research in supporting sustainable development. I hope that the presence of scholars and participants from various institutions and countries will not only enrich academic discussions but also open opportunities for future cooperation.

I would like to express my sincere appreciation to the organizing committee for their dedication in preparing this conference. May ICCRAIDS 2026 provide valuable insights, productive discussions, and meaningful partnerships that contribute to the advancement of artificial intelligence and data science for the benefit of society.

Thank you.

Dr. Agus Nur Hadie, S.Sos., M.Si.

Regional Secretary of Banyumas Regency

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6.1. Host Institution

Universitas AMIKOM Purwokerto

The International Conference on Current Research in Artificial Intelligence and Data Science (ICCRAIDS) 2026 is hosted by Universitas AMIKOM Purwokerto, Indonesia. Through its Faculty of Computer Science, the university actively promotes research, innovation, and international collaboration in the fields of artificial intelligence, data science, and digital technologies. As the host institution, Universitas AMIKOM Purwokerto plays a central role in organizing the conference and fostering a global academic platform for knowledge exchange and technological advancement.

6.2. Co-Host Institutions

ICCRAIDS 2026 is organized in collaboration with several partner universities that contribute to the academic development and international reach of the conference. The participation of these institutions reflects a shared commitment to advancing research and innovation in Artificial Intelligence and Data Science. The co-host institutions include:

Universitas Pelita Harapan (UPH)

Universitas Bunda Mulia (UBM)

Universitas Ciputra

INTI International University

Through this collaboration, ICCRAIDS aims to strengthen international academic networking and encourage interdisciplinary research cooperation among universities across the region and beyond.

6.3. Co-Sponsors

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ICCRAIDS 2026 is financially co-sponsored by the IEEE Indonesia Section, one of the regional sections of the Institute of Electrical and Electronics Engineers (IEEE). The involvement of IEEE Indonesia Section supports the conference in maintaining high academic standards, ensuring a rigorous peer-review process, and facilitating the dissemination of accepted papers through internationally recognized publication platforms.

7. COMMITTEES

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Role	Name	Affiliation
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7.3. Technical Program Committee and Reviewers

The success of ICCRAIDS 2026 relies on the valuable contributions of the Technical Program Committee and reviewers who have devoted their expertise and time to the rigorous peer-review process. Their efforts ensure the scientific quality and relevance of the accepted papers.

7.4. Senior Program Committee

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Additional reviewers and program committee members from universities, research institutions, and industry worldwide also contributed to the review process and the success of ICCRAIDS 2026.

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The Extreme Gradient Boosting (XGBoost) Model with Bayesian Optimization for Rainfall Forecasting in Ibu Kota Nusantara (IKN)

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***Abstract*—Accurate prediction of hourly rainfall in the Ibu Kota Nusantara (IKN) region is very crucial for urban planning and climate adjustment. This article studies a rigorous forecasting Extreme Gradient Boosting (XGBoost) model tuned by Bayesian optimization to predict one-step-ahead hourly rainfall intensity. The data used for developing model is meteorological data from 1979 to 2017, with careful leakage-safe preprocessing and rolling-origin validation. This study evaluates two multi-step forecasting strategies—direct and recursive. Results show that both strategies are able to predict rainfall with high accuracy. Moreover, the Bayesian optimization for tuning XGBoost hyperparameters improves predictive accuracy, i.e. reducing RMSE about 4% compared to baseline models. Additional analyses to examine extreme rainfall behaviour is given. Feature interpretability using SHAP-based importance analysis reveals that diurnal cycles, temperature persistence, and humidity fluctuations are dominant predictors. These findings demonstrate a reliable data-driven framework for rainfall nowcasting in IKN while highlighting limitations in capturing peak rainfall events.**

Keywords—Rainfall prediction, Ibu Kota Nusantara (IKN), XGBoost model, Bayesian optimization, Feature importance

I. Introduction

Recently, a climate change is a significant threat for sustainable development, causing increased volatility in weather patterns and more frequent extreme events [1]. For large-scale strategic projects such as Ibu Kota Nusantara (IKN), this uncertainty exhibits a critical challenge. To be "the most sustainable city in the world," as its core vision, managing climate-related risks—particularly extreme rainfall—is fundamental to its success [2]. Therefore, it is very demanded the ability to produce accurate rainfall forecasts for proactive planning and risk mitigation in the IKN region.

Nowadays, machine learning (ML) models have already become powerful tools for time series forecasting. It is often outperforming traditional statistical methods in capturing the complex, non-linear patterns inherent in geophysical data [3]. Among these, the eXtreme Gradient Boosting (XGBoost) algorithm has gained popularity due to its high predictive accuracy and computational efficiency [4]. However, the prediction accuracy of XGBoost is frequently dependent on hyperparameter configuration. Manual tuning is often inefficient due to several reasons such as time-consuming, labour-intensive and limited exploration of the search space. On the contrary, Bayesian optimization offers a superior alternative for finding a model's global optimum with fewer iterations [5].

In spite of the fact that XGBoost has been applied in various meteorological contexts, its application for IKN's unique microclimate—contrasting direct versus recursive forecasting strategies—remains unexplored. This article deals with this gap by proposing a robust XGBoost model enhanced with Bayesian optimization to forecast rainfall in IKN. The main goals of this study are to quantify performance improvements, evaluate forecasting strategies, and identify the most influential meteorological variables.

II. Related Works

Rainfall forecasting is a critical component of water resource management. Historically, linear statistical approaches for time series data such as Auto-Regressive Integrated Moving Average (ARIMA) and its seasonal variant (SARIMA) have served as the basis of hydrological forecasting. Previous research has demonstrated that SARIMA models are effective in capturing periodic rainfall patterns [6], though their applicability is limited by non-stationary climate dynamics. However, the applicability of these stochastic models is increasingly challenged by the impacts of climate change. Recent studies by Munir and Ismanto [6] underscores that determining accurate cropping patterns is increasingly difficult due to shifting rain patterns, which violate the stationarity assumptions required by traditional linear models. As a result, these models often fail to capture the high stochasticity and complex non-linear dynamics in tropical meteorological data.

To cope with these drawbacks, Machine Learning (ML) algorithms have emerged as robust alternatives which is capable of modelling complex non-linear relationships without strict stationarity assumptions. Early implementations using Artificial Neural Networks (ANN) and Support Vector Regression (SVR) demonstrated superior capabilities compared to ARIMA. For instance, Liu and Zio [7], showed the effectiveness of hyperparameter-tuned SVMs for recursive multi-step predictions. Despite their success, these models can be computationally intensive and prone to overfitting when dealing with high-dimensional temporal data.

A significant progress in predictive modelling was the introduction of eXtreme Gradient Boosting (XGBoost) by Chen and Guestrin [4]. As a scalable implementation of the Gradient Boosting Decision Tree (GBDT) framework, XGBoost employs a regularized objective function that penalizes model complexity to enhance generalization capabilities. In the context of hydrology, XGBoost has shown to consistently outperform traditional ML models in hourly rainfall forecasting. Its specific advantages include the ability

to handle missing values automatically—a common issue in sensor-based weather data—and its efficiency in learning complex feature interactions through tree-based ensembles.

Nevertheless, the performance of XGBoost often depends on its hyperparameter configuration (e.g., learning rate, tree depth, regularization terms etc.). For high-dimensional parameter spaces, traditional tuning methods, such as Grid Search or Random Search, are usually inadequate due to computationally expensive and inefficient. To overcome this, Bayesian optimization has emerged as a state-of-the-art method for automatic model tuning. This approach, as described by Snoek et al. [5], utilizes a probabilistic surrogate model (typically a Gaussian Process) to balance exploration (searching new regions) and exploitation (refining promising regions). This study exploits this advanced optimization method to tune the XGBoost hyperparameters specifically for the microclimatic conditions of IKN.

III. METHODS

A. Data Source and Pre-processing

This study makes uses of historical meteorological data for the Ibu Kota Nusantara (IKN) region, covering the period from January 1, 1979 to December 31, 2017. The dataset was from "DATAQUEST," a national data science competition organized by the Faculty of Advanced Technology and Multidiscipline (FTMM) at Airlangga University. Based on its temporal coverage beginning in 1979, hourly resolution, and the range of atmospheric variables provided, the dataset indicates features compatible with global climate reanalysis products such as ERA5 [8], although the precise origin was not clearly stated by the competition organizers. The variables in the data are 10 predictor variables: temperature (*temp*), dew point (*d_point*), the perceived temperature in Celsius as felt by the human body (*feels)*, minimum temperature (*min temp*), maximum temperature (*max temp*), humidity (*hum*), pressure (*prssr*), wind speed (*wind_spd*), wind direction (*wind_deg*), cloud cover (*clouds*), and one target variable, hourly rainfall (*rain_1h*). To simulate the complexities of real-world data pipelines, the organizers introduced noises and anomalies into the dataset. These anomalies on the data, such as inconsistent unit strings within numerical columns and missing values, required preprocessing to be clean and standardize prior to feature engineering and model training.

B. Feature Engineering

At first, a thorough feature engineering process was implemented to transform the raw time series data into a supervised learning format fitted for XGBoost [9]. All engineered features were set up entirely from past observations to ensure temporal validity. The simultaneous values of all predictor variables at time *t* were ruled out from the input space, since these would not be available in a real forecasting scenario. Then, the lag order and rolling window size were determined empirically from the Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of the training data, as shown in Figure 1. The PACF showed that the dominant autocorrelation is at lag-1, while the ACF showed a significant correlation up to lag-3. Therefore, a lag depth of 3 was selected as the basis for establishing autoregressive features.

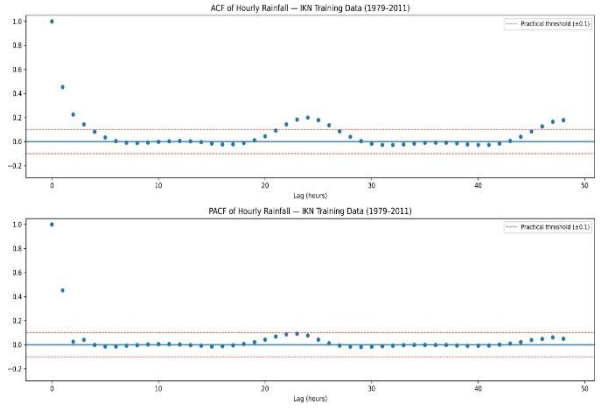

Fig. 1. ACF and PACF of hourly rainfall in the IKN training data (1979–2011).

Starting from 10 meteorological predictor variables, the following four techniques were applied [10, 11]:

1. Time-Delay Embedding (Lag Features) is used to capture autoregressive dependencies. For each of the 10 predictor variables, lagged values were set up for the preceding three-time steps (lag-1 through lag-3), resulting in total 30 lag features.
2. Rolling Window Statistics is utilized to capture local trends and short-term variability. To each predictor variables, the mean, standard deviation, maximum, and minimum were computed over a 6-hour rolling window. This produced 40 rolling features. The 6-hour window was derived from the diurnal signal observed in the ACF at approximately lag-24. It captured sub-diurnal convective dynamics characteristic of the equatorial climate in IKN.
3. Differencing is to capture the rate of change over time. To each predictor, first-order differencing and seasonal differencing with a 24-hour lag were applied, producing 20 differencing features. The 24-hour seasonal lag indicates the strong daily rainfall cycle typical of tropical rainforest climates.
4. Calendar-Based Time Features is used to encode temporal periodicity. From the datetime index, the hour of day, day of week, month, week of year, and year were extracted. To preserve the circular continuity (e.g., ensuring hour 23 and hour 0 are treated as adjacent), cyclical encoding using sine and cosine transformations was applied to the hour, day of week, and month. This process yielded 13-time features in total.

As a result, the original 10 predictor variables were enlarged to 103 input features for the model (i.e. 30 lag features, 40 rolling statistics, 20 differencing features, and 13 calendar-based time features). The concurrent observed values of all predictor variables at time *t* were excluded from the input space to prevent data leakage.

C. XGBoost

The Extreme Gradient Boosting (XGBoost) algorithm proposed by Chen & Guestrin [4] is a powerful and highly efficient ensemble learning method. It is based on a serial decision tree such that each new tree improves the prediction of the former. For example, if the model consists of *K* trees,

the final prediction for x_i is the sum of the outputs from K individual trees, where each tree is an independent function f as shown in (1).

$$\hat{y}_i = \sum_{k=1}^{K} f_k(x_i) \quad (1)$$

To learn the set of decision trees, the model minimizes the following regularized objective function as in (2), which balances model accuracy with complexity:

$$\mathcal{L} = \sum_{i=1}^{n} l(y_i, \hat{y}_i) + \sum_{k=1}^{K} \Omega(f_k) \quad (2)$$

This objective consists of two primary components. The first is the loss function, l, which measures the difference between the actual target y_i and the predicted value $\hat{y}_i$. The second component is the regularization term, Ω, which penalizes model complexity to prevent overfitting. For a single tree f_k, this term is defined as (3):

$$\Omega(f_k) = \gamma T + \frac{1}{2}\lambda \sum_{j=1}^{T} w_j^2 \quad (3)$$

where T is the number of leaves in the tree, w_j is the score of the j-th leaf, and γ and λ are regularization parameters. Since the model in (2) includes functions as parameters, it cannot be optimized using traditional methods. Instead, XGBoost is trained in an additive manner. The prediction at iteration t is the prediction from the previous step $t-1$ plus the contribution of a new tree, f_t, which is given in (4):

$$\hat{y}_i^{(t)} = \hat{y}_i^{(t-1)} + f_t(x_i) \quad (4)$$

To find the best new tree f_t to add at each step, the algorithm optimizes an objective function that has been approximated using a second-order Taylor expansion around the prediction $\hat{y}_i^{(t-1)}$ using (5):

$$\mathcal{L}^{(t)} \approx \sum_{i=1}^{n} \left[g_i f_t(x_i) + \frac{1}{2} h_i f_t^2(x_i) \right] + \Omega(f_t) \quad (5)$$

where g_i and h_i are the first and second-order gradient statistics (the gradient and Hessian) of the loss function with respect to the prediction at step $t-1$. This formulation allows for rapid and parallelizable optimization, enabling XGBoost to find high-performing models efficiently while controlling for overfitting through regularization, making it a robust choice for complex forecasting tasks.

D. Bayesian Optimization

Hyperparameter tuning is treated as a "black-box" optimization problem, where the objective function $f(x)$ is unknown and expensive to evaluate. We aim to find the global minimum x^* within a search space X. To achieve this efficiently, we use Bayesian Optimization, which constructs a probabilistic surrogate model to map the input parameters to the objective score [12]:

1. We use a Gaussian Process (GP), a non-parametric model as the surrogate model to define a probability distribution over functions. It is based on the assumption that the function values $f(x)$ at different points are correlated depending on their distance in the search space. Equation (6) describes a GP that is fully specified by a mean function $m(x)$ and a covariance (kernel) function $k(x, x')$:

$$f(x) \sim \mathcal{GP}\big(m(x), k(x, x')\big) \quad (6)$$

The kernel function represents our assumptions about the smoothness and rate of change of the objective function. For given observed data points, the GP will provide a posterior distribution for any candidate point x, providing both a predicted mean $\mu(x)$ and an uncertainty estimate $\sigma(x)$ (standard deviation).

2. To determine which hyperparameter configuration to evaluate next, we employ an acquisition function (also known as a policy). This function balances two competing goals, i.e. exploitation (examining low predicted error areas) and exploration (examining high uncertainty areas). In this study, we utilize the Expected Improvement (EI) policy shown in (7) to select the next point x_{t+1} by maximizing the expectation of improvement over the current best observed value $f(x^*)$:

$$\alpha_{EI}(x) = E[\max(f(x^*) - f(x), 0)] \quad (7)$$

This strategy enables the optimizer to efficiently scan the search space and find the optimal hyperparameters in a significantly fewer iterations than random or grid search methods.

E. Implementation and Forecasting Strategies

The XGBoost model was implemented using the XGBRegressor object from the XGBoost Python library. To ensure a temporally valid evaluation, the dataset was split chronologically into a training set (1979–2011) and a test set (2012–2017), with no random shuffling applied. Prior to training, all input features were standardized using StandardScaler from scikit-learn, fitted exclusively on the training set and subsequently applied to the test set to prevent data leakage. The target variable (rain_1h) was left in its original unit (mm/hour) and not subject to any scaling transformation. Therefore, all reported error metrics (MAE and RMSE) are in mm/hour.

Only lagged values of the meteorological predictors (lag-1 through lag-3), their rolling statistics over a 6-hour window, first-order and seasonal differences, and calendar-based time features were retained as model inputs to prevent information leakage from the target variable. The simultaneous observed values of all predictors at time *t* were omitted, for these would not be available in a real forecasting scenario.

An internal validation set covering 2009–2011 was extracted from the training period for hyperparameter optimization. The Bayesian optimization process using Optuna's GPSampler evaluated each of the 50 trials against this validation set exclusively, ensuring the test set remained untouched throughout the tuning process. Once the optimal hyperparameters were identified, the final model was retrained on the full training period (1979–2011) before being evaluated on the test set.

Two multi-step forecasting strategies were developed and compared [13]:

- Direct Strategy: A single model was trained on the full training dataset and used to generate predictions for the entire test set in one pass, with no parameter updates during inference.
- Recursive (Rolling) Strategy: The model was first trained on the training data, then predictions were generated in sequential batches of three months (2,160 hours). After each batch, the actual observed values from that batch were appended to the training history and the model was retrained before proceeding to the next batch.

Combining default and Bayesian-optimized configurations across both strategies yields six experimental scenarios in total.

F. Hyperparameter Optimization

To find the optimal model configuration, Bayesian optimization was employed using the Optuna library [14], specifically with the GPSampler which utilizes Gaussian Processes. The optimization was run with two scenarios: first is using 25 and 50 trials. The important XGBoost hyperparameters and their search spaces are given in Table I.

TABLE I. HYPERPARAMETER SEARCH SPACE FOR BAYESIAN OPTIMIZATION

Hyperparameter	Search Range	Description
n_estimators	100 – 6000	Number of boosting rounds
max_depth	4-8	Maxium tree depth
learning rate	0.001 – 0.3	Step size shrinkage
subsample	0.6 – 1.0	Fraction of training samples
colsample_bytree	0.6 – 1.0	Fraction of features per tree
colsample_bylevel	0.6 – 1.0	Fraction of features per tree depth level
colsample_bynode	0.6 – 1.0	Fraction of features per node split
reg_alpha (L1)	0.0 – 10	L1 regularization term
reg_lambda (L2)	0.0 – 20	L2 regularization term
gamma	0.0 – 1.0	Minimum loss reduction

G. Evaluation Metrics

Two standard regression metrics, i.e. Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are evaluated to compare the predictive accuracy of all model scenarios. The MAE defined in (8) as the average of the absolute differences between the predicted and actual values provides a measure of the average magnitude of the errors.

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{8}$$

On the other hand, the RMSE in (9), the square root of the average of the squared differences between predicted and actual values, gives a higher weight to larger errors. Thus, it is particularly sensitive to large prediction mistakes.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{9}$$

where :

- n is the number of data points in the test set.
- y_i is the actual (observed) rainfall value for the i-th data point.
- $\hat{y}_i$ is the predicted rainfall value for the i-th data point.

IV. RESULTS AND DISCUSSION

A. Model Performance Evaluation

The six proposed scenarios mixing default and optimized models with both direct and recursive strategies were evaluated on the test set. To contextualize the results, two naive baselines were also included: a persistence model, which predicts that the next hour's rainfall equals the current hour's observed value, and a climatology model, which predicts the long-term hourly mean from the training period. Their MAE and RMSE are presented in Table II.

Furthermore, the application of Bayesian optimization resulted in a consistent improvement in predictive accuracy across all scenarios. From Table II, the best-performing model overall is the XGBoost model optimized with 50 trials using the recursive strategy, achieving an RMSE of 0.8596 mm/hour and an MAE of 0.4246 mm/hour. This represents a reduction of approximately 3.4% in RMSE compared to the default recursive model (0.8898 mm/hour). Both baseline models — persistence (RMSE: 1.0115 mm/hour) and climatology (RMSE: 0.9376 mm/hour) — are substantially outperformed by all XGBoost configurations, confirming the model's ability to capture non-linear meteorological dynamics beyond simple statistical references. Interestingly, the 25-trial direct configuration achieved the lowest RMSE among the direct strategy models (0.8627 mm/hour), slightly outperforming its 50-trial counterpart (0.8631 mm/hour), suggesting that beyond a certain number of trials the optimization may converge to configurations overly specialized to the internal validation period. Both strategies produced closely competitive results, with the recursive method showing a marginal advantage in the optimized configurations.

TABLE II. PERFORMANCE EVALUATION OF XGBOOST MODELS ON THE TEST SET (2012-2017)

Model Scenario	MAE	RMSE
Default – Direct	0.4361	0.8851
Default – Recursive	0.4424	0.8898

Optimized (25 Trials) – Direct	0.4220	0.8627
Optimized (25 Trials) – Recursive	0.4279	0.8640
Optimized (50 Trials) - Direct	0.4221	0.8631
Optimized (50 Trials) - Recursive	0.4246	0.8596

The following Table III gives the optimal hyperparameters for the two best models (50 trials direct and recursive) in more detail.

TABLE III. OPTIMAL HYPERPARAMETERS FOR THE 50-TRIAL OPTIMIZED MODELS

Hyperparameter	Direct	Recursive
n_estimators	4443	4784
max_depth	8	8
learning rate	0.01033	0.00633
Subsample	0.6	0.6
colsample_bytree	0.6	0.65686
colsample_bylevel	0.6	0.69804
colsample_bynode	0.6	1
reg_alpha (L1)	10	10
reg_lambda (L2)	20	20
Gamma	0	0.185

Further analysis of the optimal hyperparameters given in Table III shows that the Bayesian optimization process converged on different configurations for the direct and recursive strategies. The most noticeable different is in the regularization parameters, i.e. the L2 regularization term (*reg_lambda*) increased from 0 for the direct model to 20 in the recursive model. This matter indicates that the optimizer effectively recognized and counteracted for the higher intrinsic risk of overfitting in the recursive strategy by retraining on an accumulating dataset iteratively.

On the contrary, other parameters such as gamma and max_depth remained constant across both models (gamma = 1.0, max_depth = 8). It is also important to note that the optimal configuration of the recursive model employed a larger ensemble (n_estimators = 4784). When combined with a lower learning rate (0.006), this indicates a more granular and incremental learning process suitable for the iterative retraining nature of the recursive strategy. Simultaneously, these results reveal the ability of Bayesian optimization to adapt highly specific hyperparameter configurations for each forecasting methodology.

To evaluate rainfall detection capability and extreme event performance, Table IV presents the F1-score, Precision, Recall, and RMSE for the 95th percentile extreme rainfall subset (threshold: 2.28 mm/hour) across all model scenarios. A rainfall occurrence threshold of 0.1 mm/hour was used to convert predictions to binary rain/no-rain labels for classification metrics.

TABLE IV. CLASSIFICATION AND EXTREME EVENT PERFORMANCE METRICS

Model Scenario	F1	Precision	Recall	RMSE (P95)
Persistence	0.7724	0.7724	0.7724	3.2224
Climatology	0.5638	0.3926	1.0000	3.6614
Direct — Default	0.6467	0.5101	0.8834	3.2929
Direct — 25 Trials	0.6543	0.5119	0.9065	3.2718
Direct — 50 Trials	0.6558	0.5179	0.8938	3.2537
Recursive — Default	0.6447	0.5051	0.8909	3.2877
Recursive — 25 Trials	0.6491	0.5026	0.9160	3.2708
Recursive — 50 Trials	0.6536	0.5082	0.9153	3.2454

B. Feature Importance Analysis

To determine the most important variables in the accuracy of prediction a feature importance analysis need to be done. Although the recursive model reached a slightly lower RMSE, the feature importance analysis was performed on the optimized direct model (50 trials). This is done due to its significantly more favourable computational profile, i.e. its one-shot training. Additionally, the prediction process is significantly faster and less resource-intensive than the iterative retraining demanded by the recursive strategy. The importance scores for the top 10 predictors for this model are shown in Figure 2.

From the figure, it can be seen that no single variable excessively dominates the prediction. Instead, a mixture of temporal, meteorological, and engineered features contributes to the final forecast. Temporal information dominates the top predictors: the sine-encoded hour of the day (hour_sin) emerged as the most influential feature (6.5%), followed by the raw hour feature (4.2%), together confirming the strong diurnal rainfall cycle characteristic of the tropical IKN climate. In the third position with about 2.6% is the one-hour lagged temperature, temp_lag1. It is closely followed by the cosine-encoded hour, hour_cos, (2.5%), which further reinforcing the role of temporal periodicity. Among meteorological features, two-hour lagged wind speed (wind_spd_lag2, 2.2%), humidity change (hum_diff, 1.9%), one-hour lagged cloud cover (clouds_lag1, 1.8%), dew point change (d_point_diff, 1.7%), three-hour lagged wind speed (wind_spd_lag3, 1.4%), and temperature change (temp_diff, 1.3%) complete the top 10. This emphasizes the model's dependence on recent atmospheric conditions and established

daily patterns. Furthermore, the multifactorial nature of rainfall in the IKN region is indicated by the relatively uniform distribution of importance scores across the top features. Thus, for accurate prediction a comprehensive feature set is required.

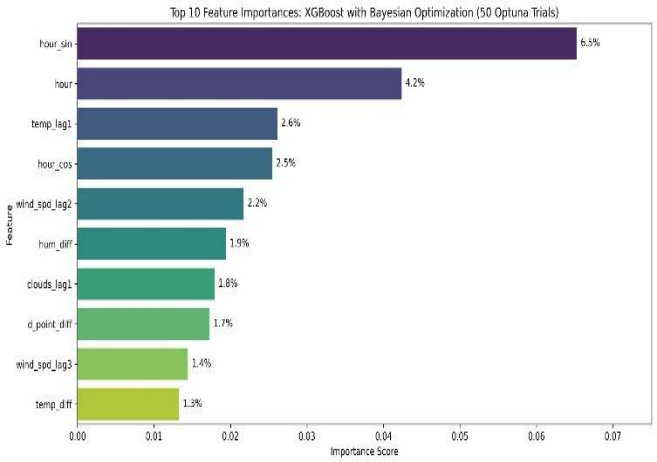

Fig. 2. The top 10 most important features determined by the final optimized XGBoost model.

Futhermore, from Figure 3, the SHAP summary plot show that temporal feature (i.e. hour sin, hour) have strongest influence on the model predictions. This indicates that time-of-day patterns dominate the model behavior. Weather related variables (e.g. cloud lag1, temp lag1, d point diff) contribute with moderate and variable effects. On the other hand calendar feature (e.g. week of year, year) have relatively minor impact. Overall, the model is mainly driven by daily temporal dynamics with meteorological variables providing secondary adjustmens.

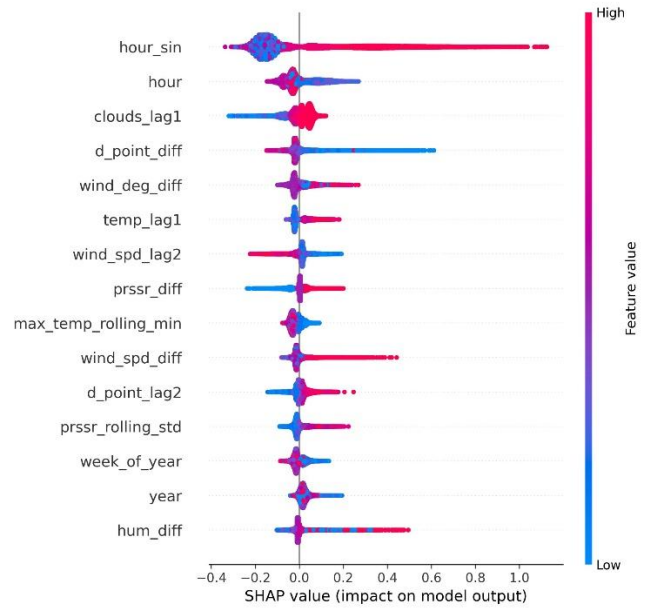

Fig. 3. SHAP summary plot for the best recursive model (50 trials). Features ranked by mean absolute SHAP value; colour indicates feature value magnitude (red=high, blue=low).

C. *Discussion*

The empirical results of this study strongly validate that the Bayesian optimization is an effective method for enhancing the predictive performance of the XGBoost model. Although at first the ~4% reduction in RMSE may appear modest, such minor improvements are often operationally significant in meteorological forecasting. The competitive performance between the direct and recursive strategies gives some insights. First, it indicates that the risk of catastrophic error propagation in the recursive model for the temporal horizon of this study was minimal. Secondly, for deployment in resource-constrained environments, a direct forecasting strategy is more advantageous due to efficient computation without sacrificing predictive accuracy substantially

The high importance attributed to the hour feature confirms that the expected strong daily cycle characteristic of tropical climates, i.e. rainfall, is often time-dependent. Figure 4 shows the comparison of the optimized model prediction for test data (from 2012 to 2017) and the actual monthly rainfall. Overall, the graph indicates that the proposed model successfully captures rainfall trend and seasonal variabilities as the predicted curve closely follow the observed data.

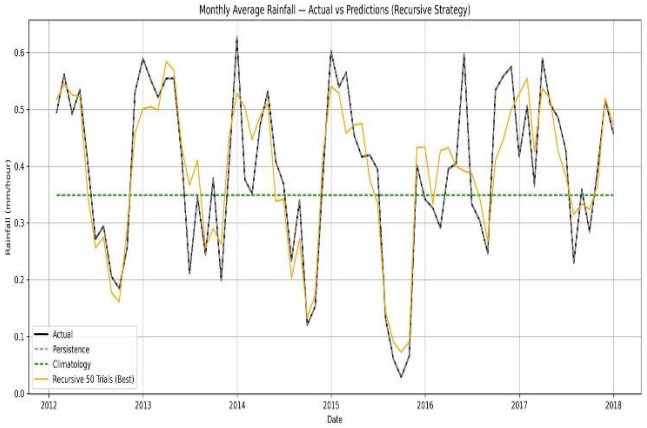

Fig. 4. Monthly average rainfall: actual vs. recursive strategy predictions (2012–2017). The XGBoost model tracks seasonal variability while the climatology baseline (flat green line) cannot.

In spite of the model's overall success in capturing general seasonal patterns, quantitative analysis of prediction residuals reveals some limitations. From Figure 5, an analysis of the target variable distribution showed that 59.9% of hourly observations recorded zero rainfall, while only 5.0% exceeded the 95th percentile threshold of 2.28 mm/hour. This highly zero-inflated distribution explains the relatively low precision scores (~0.51) observed across all XGBoost configurations. There is an indication that the class imbalance causes the model to generate false positives when predicting rainfall occurrence. For extreme events exceeding the P95 threshold, the best recursive model achieves an RMSE of 3.2454 mm/hour compared to an overall RMSE of 0.8596 mm/hour, reflecting the inherent difficulty of learning from rare high-intensity events as shown in Figure 6. The 50-trial recursive configuration yields the best extreme event RMSE (3.2454), while the 25-trial direct configuration achieves the best F1-score (0.6543) and highest recall (0.9065), indicating a strategy-dependent trade-off between classification accuracy and regression precision. Future work could address extreme event underestimation through threshold-weighted loss functions, hybrid classification-regression approaches, or deep learning architectures such as Long Short-Term Memory (LSTM) networks or Transformers designed for long-range dependency learning.

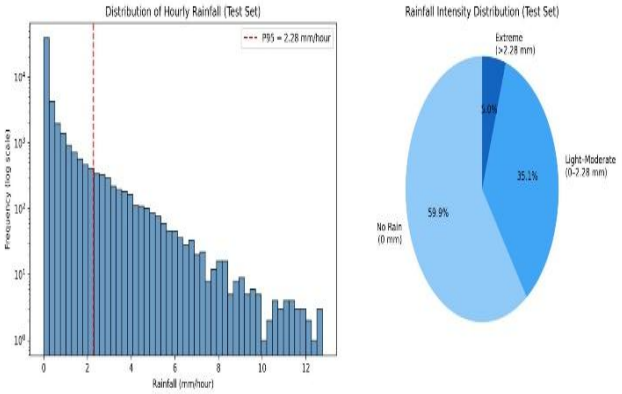

Fig. 5. Distribution of hourly rainfall in the test set (2012–2017). Left: histogram (log scale) with P95 threshold at 2.28 mm/hour. Right: proportional breakdown showing 59.9% no-rain, 35.1% light-moderate, and 5.0% extreme events.

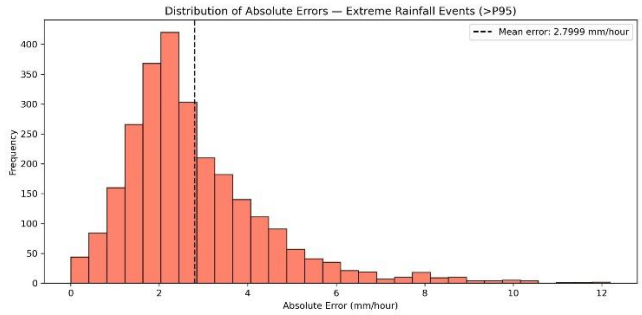

Fig. 6. Distribution of absolute prediction errors for extreme rainfall events (>P95 = 2.28 mm/hour) using the best recursive model (50 trials). Mean absolute error = 2.80 mm/hour; right-skewed distribution indicates systematic underestimation of peak events.

D. Conclusion

This study shows that XGBoost method forecast rainfall in IKN region very accurate. In addition, the application of Bayesian optimization successfully improves predictive accuracy in comparison to a default model configuration. A further analysis also indicates that both direct and recursive forecasting strategies yield high-performance results. Nevertheless, for practical applications the simpler direct strategy provides a more computationally efficient alternative method with only a minor trade-off in accuracy. On the other hand, the most influential predictor variables in this study are temporal indications, such as the hour of the day, and recent atmospheric conditions. This emphasizes the importance of a comprehensive feature engineering process. At last, this work also provides a powerful, data-driven forecasting framework that is a valuable tool for policymakers and stakeholders for supporting climate adaptation and strategic planning. Therefore, the development of Indonesia's new capital can be sustained. For future works, a hybrid of XGBoost and Deep Learning architectures (e.g., LSTM-XGBoost) can be explored to better capture extreme weather anomalies [15].

The **first author** conducted the primary research, including the study design, data analysis, and preparation of the manuscript. The **second author** contributed to the research design, provided technical guidance, and reviewed and revised the manuscript.

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