



Calibration and Evaluation of GPM Satellite Rainfall for Estimating Annual Maximum Rainfall at Ungauged Sites in the Rea Watershed

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Abstract: Limited rain gauge coverage and uneven station distribution remain major challenges for hydrological analysis in ungauged watersheds. This study calibrated and evaluated GPM IMERG satellite rainfall for estimating annual maximum daily rainfall (AMS) in the Rea Watershed, Indonesia. AMS data from four rain gauge stations (Tepas, Taliwang, Seteluk, and Pototano) were used as ground observations, while nine GPM grid cells represented spatial rainfall over the watershed. A rainfall-range-based multiplicative correction was applied using gauge-satellite AMS pairs. Performance was evaluated using Percent Bias (PBIAS), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Sum of Squared Errors (SSE), followed by leave-one-station-out (LOSO) validation. Uncorrected GPM data showed systematic underestimation, with PBIAS of -17.7%, RMSE of 66.64 mm, and MAE of 48.67 mm. After optimized correction, PBIAS shifted to +13.8% and MAE slightly improved to 47.97 mm, but RMSE increased to 75.82 mm and SSE to 201,213 mm². These results indicate that the correction reduced bias but did not improve overall accuracy. LOSO validation produced RMSE values of 50.83-72.13 mm, indicating sensitivity to station omission. Overall, GPM rainfall can support preliminary AMS estimation in ungauged areas, but its application should be treated cautiously because of persistent uncertainty in extreme rainfall estimation.

Keywords: Annual maximum series; Bias correction; GPM IMERG; Rea Watershed; ungauged catchments.

Introduction

Reliable rainfall data with sufficient spatial representativeness are critical for hydrological studies, especially extreme rain fall estimation, flood mitigation as well as water-resources planning (Kidd & Huffman, 2011; Tapiador et al., 2012; Beck et al., 2017 and Hinge et al. (2022) For example, in many watersheds such as Indonesia, rain-gauge networks are still sparse and their distributions uneven leading to uncertainty when point observations are employed to capture basin-scale rainfall, specifically regarding extremes (Hidayah et al., 2022; Haromain et al., 2022; Ramadhan et al., 2022; Maggioni & Massari, 2018; Beck et al., 2019; Dong et al., 2022). This situation also occurs in the case of Rea Watershed with more gauges located at middle and

downstream areas, whereas upstream part is still ungauged (Lismula et al., 2021; Putra, 2024). The upstream area is also physically complex because topography and orographic processes can enhance local rainfall, and increase spatial variability that further complicates rainfall estimate in ungauged headwaters (Barros & Lettenmaier, 1994; Roe, 2005; Houze & Medina, 2005; Houze, 2012; Dinku et al., 2007; Dinku et al., 2008; Xu et al., 2017).

Satellite-derived precipitation provides a viable alternative as rainfall information can be provided continuously across space, including in regions which suffer from data scarcity (Kidd & Huffman, 2011; Hou et al., 2014; Skofronick-Jackson et al., 2017; Huffman et al., 2020). Among them, GPM IMERG is commonly used while raw estimates still present systematic biases

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particularly at daily scale, in complex terrain and during high-intensity rainfall events (Tang et al., 2016; Asong et al., 2017; Bogerd et al., 2021; Jiang et al., 2023; Liu et al., 2020; Hutagaol et al., 2023). Hence, GPM still needs to be validated and calibrated locally before being deployed in hydrological studies (Maggioni et al., 2016; Maggioni & Massari, 2018; Hinge et al., 2022). This is most relevant to Annual Maximum Series (AMS) analysis that is frequently applied in hydrologic design and frequency analysis as it concerns the maximum rainfall event in each year (Coles, 2001; Katz et al., 2002; Koutsoyiannis, 2004a; Koutsoyiannis, 2004b; Martins & Stedinger, 2000). Due to AMS relying on the upper tail of the rainfall distribution, a bias in extreme satellite rainfall directly affects design-rainfall estimates yet statistical bias-correction methods have been shown to enhance performance of satellite-based rainfall both as a whole and against intensity-dependent (Piani et al., 2010; Gudmundsson et al., 2012; Lober et al., 2023; Li et al., 2023) and topographic error (Yang et al., 2024; Du et al., 2024).

So far, the potential of GPM has been assessed during the regional evaluation in Indonesia (Sanjaya et al., 2022; Liu et al., 2020) and found that there was performance to be obtained even though according to the results of other studies, it tends to be location specific and needs to be evaluated at watershed scale before it can be used operationally Ramadhan et al. (2022); Hutagaol et al. (2023). There are not yet specific studies on the potential of GPM calibrated to estimate ungauged upstream areas' maximum annual daily rainfall in the Rea Watershed (Lismula et al., 2021; Putra, 2024). Hence, the objective of this study is to calibrate and evaluate GPM rainfall for annual maximum daily rainfall estimate in Rea Watershed and analyze its suitability in ungauged headwaters. This study is unique in linking local GPM calibration with AMS-based extreme-rainfall analysis, applied to topographically complex ungauged upstream areas of the Rea Watershed, providing local people with more reliable data for flood mitigation and hydraulic design (flood routing), watershed planning.

Method

Research Design

The study used a quantitative evaluative approach to evaluate the appropriateness of satellite-derived rainfall information for estimating annual maximum daily rainfall in ungauged catchments. The methodological framework included extracting annual maximum series (AMS) from rain gauge and satellite datasets, then calibrating satellite rainfall with respect to the observed gauge records. The accuracy and reliability of the calibrated satellite estimates were assessed and validated. Lastly, the validated correction method was

applied to ungauged upstream locations under tentative consideration for its applicability in data-poor regions. For the sake of clarity, a flowchart illustrating the methodological procedure is shown in Figure 1. Such a framework is similar to usual methods used for satellite precipitation validation over regions that are sparsely equipped with ground observations (Tian et al., 2010; Omrani et al., 2022; Andari & Nurhamidah, 2024; Tulistiawan et al., 2023).

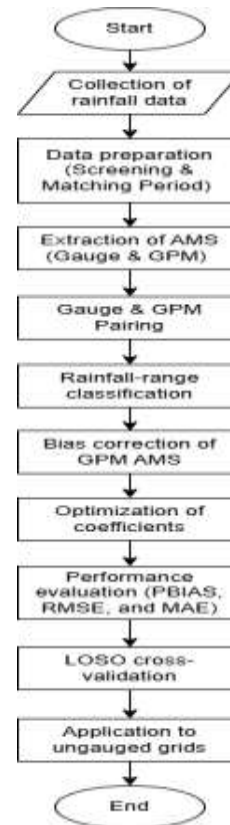


Figure 1. Flowchart of the methodological framework

Study Area and Data Sources

The study was conducted in the Rea Watershed, one of the watersheds that belong to Sumbawa River Basin, Indonesia. The rain gauge coverage in the watershed is very sparse, with most of the gauge stations located in the middle or downstream areas while the upstream has no gauged station (Lismula et al., 2021). The ground reference data consisted of four operational rain gauge stations in Tepas, Taliwang, Seteluk, and Pototano (Figure 2).

We obtained satellite rainfall from the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) product that provides quasi-global near real-time precipitation estimates with a spatial resolution of 0.1° (Huffman et al., 2018). This product has been extensively used in multi-hydrological studies, notably over regions with poor observation networks (Hou et al., 2014; Skofronick-

Jackson et al., 2017). The IMERG applicability has also been reported in Indonesia, such as Bali and Nusa Tenggara (Tulistiawan et al., 2023), Bima and Dompu (Rostihanji & Saidah, 2023), Lau Simeme Watershed (Hutagaol et al., 2023) and Indonesian Maritime Continent (Ramadhan et al., 2022) which have shown its wide-scale rainfall useful but still needs to be validated locally for hydrological use. The analysis included nine GPM grid cells that covered the Rea Watershed. Standard AMS protocols for extreme-rainfall analysis were then applied to daily rainfall from both gauged and GPM-data locations to determine series of annual maximum daily rainfall (Katz et al., 2002; Gao et al., 2023).

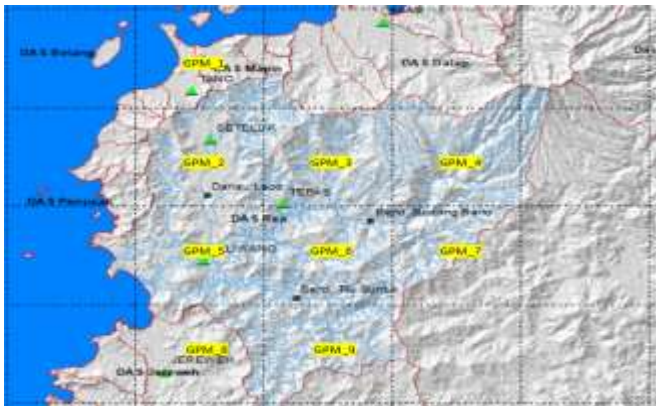


Figure 2. Location

Pairing of Rain Gauge and Satellite Rainfall Data

The rain gauge and satellite rainfall data were matched on the spatial level by assigning each rain gauge to its nearest GPM grid cell. This is a standard practice for precipitation validation (Beck et al., 2017). For gauges entirely within a single GPM pixel, rainfall values were directly taken from that grid. Average rainfall values from relevant neighboring pixels were used to account for some local spatial variability particularly in areas near to grid boundaries (Tan et al., 2020). It is also worth noting that similar gauge-satellite comparison schemes have been applied in Indonesian works validating IMERG and other satellite rainfall products at watershed and regional scales (e.g. Andari & Nurhamidah, 2024; Sulistiyono & Fadli, 2023; Sanjaya et al., 2022).

Satellite Rainfall Bias Correction

In order to minimize systematic biases inherent in the GPM-derived AMS values, a multiplicative scaling based on rainfall range was applied. Satellite rainfall estimates were divided into several ranges of rainfall intensities, and a valid correction coefficient was assigned for each range in this method. This range-dependent correction has also been applied extensively in reducing systematic errors of satellite precipitation

products (Themefsl et al., 2011; Fang et al., 2019). Studies in Indonesia have found that raw IMERG estimates typically need adjustments before they can be applied for hydrology, and that their agreement with measured rainfall is better after adjusting using regression or ratio (Rostihanji & Saidah, 2023; Andari & Nurhamidah, 2024; Mamenun et al., 2014). Corrected Rainfall was calculated as:

$$P_{corr} = c_k \cdot P_{sat} \tag{1}$$

where P_{corr} denotes corrected rainfall, P_{sat} uncorrected GPM rainfall, and c_k the scaling factor for intensity bin k .

Correction Coefficient Optimization

During calibration, the correction coefficients were estimated by minimizing the residual difference between homogeneous paired satellite and observed AMS values. This kind of parametric adjustment is common due to its relative simplicity and computational efficiency (Müller & Thompson, 2013). The appropriate coefficient for each rainfall range was determined by the following expression:

$$c_k^* = \frac{\sum(P_{sat} \cdot P_{obs})}{\sum(P_{sat}^2)} \tag{2}$$

where P_{obs} denotes the observed AMS from rain gauge data. For rainfall classes with insufficient observations, a basin-wide mean correction coefficient was used to reduce the risk of overfitting (Beck et al., 2017; Tan et al., 2020). The need for local calibration is also supported by Indonesian studies showing that GPM/IMERG performance varies substantially across regions, seasons, and rainfall intensities (Tulistiawan et al., 2023; Hutagaol et al., 2023; Ramadhan et al., 2022).

Performance Metrics

Using Percent Bias (PBIAS), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) the result of raw GPM rainfall were compared against rain gauge observations, as well as corrected GPM rainfall. These metrics were chosen because they offer different perspectives on systematic bias and the magnitude of overall error (Moriassi et al., 2007; Tian et al., 2018). Their application is also in line with recent evaluations of GPM/IMERG products conducted by Indonesia in Kuranji, Lau Simeme, Bima-Dompu and Bali-Nusa Tenggara (Andari & Nurhamidah, 2024; Hutagaol et al., 2023; Rostihanji & Saidah, 2023; Tulistiawan et al., 2023).

Leave-One-Station-Out Cross-Validation

Leave-one-station-out (LOSO) cross-validation was employed to evaluate the potential transferability of the

correction method under ungauged conditions. With each iteration, one rain gauge station was omitted from calibration; correction coefficients were re-estimated based on the remaining stations and model performance was evaluated at the excluded station. This is a common procedure used to provide model conditions for predicting ungauged catchments, and assessing the robustness of the regionalization techniques (Merz & Blöschl, 2004; Zhang et al., 2021). A Monte Carlo validation in Bandung Raya has also been conducted using cross-validation-based evaluation of satellite rainfall (Sanjaya et al. 2022).

Extrapolation to Ungauged Locations

Following validation, the optimized correction coefficients were used to compute maximum annual daily rainfall in ungauged upstream areas using GPM grid cells distributed throughout the Rea Watershed. This step enabled spatially extending the corrected rainfall information in the data-sparse region of the watershed (Beck et al., 2019; Gao et al., 2023). Such motivations have also been reported in Indonesian studies where satellite rainfall products are adopted to supplement scant rain gauge networks and provide additional data for a hydrological analysis in poorly observed watersheds (Andari & Nurhamidah, 2024; Hutagaol et al., 2023; Ramadhan et al., 2022). However, results from extrapolation were interpreted with caution because rainfall-generation mechanisms and satellite error characteristics may differ between upstream mountainous regions and low-elevation gauged basins.

Result and Discussion

The respective performances of each of the three correction scenarios are given in Table 1 and illustrated in Figure 3. The lowest RMSE (66.64 mm) and SSE (155430 mm²) were obtained from uncorrected GPM data with optimized correction yielding the highest values for both RMSE (75.82 mm) and SSE (201213mm²). Thus, even though the optimized correction slightly reduced MAE from that obtained for the initial correction (decrease of 21.1% recommended) it still yielded similar agreement to uncorrected data in terms of overall error magnitudes. Thus, the correction procedure should not be understood as a technique in our case to increase overall accuracy according to Table 1 and Figure 3; instead, it modified primarily the bias pattern of the satellite estimates.

The bias pattern in Table 1 also demonstrates an overcorrection effect. The negative PBIAS of -17.7% for uncorrected GPM rainfall indicates that the satellite data significantly underestimated annual maximum daily rainfall. After post-optimization, however the PBIAS also shifted to +13.8%, meaning that the adjustment

shifted these estimates above target resulting in overestimation. This movement from negative to positive bias (Table 1 and Figure 3) indicates that the rainfall-range correction was too intense, particularly at high total rainfall values.

Table 1. Performance statistics of GPM satellite rainfall for AMS estimation

Model	PBIAS (%)	RMSE (mm)	MAE (mm)	SSE (mm ²)
Uncorrected	-17.7	66.64	48.67	155430
Initial correction	-6.5	81.56	54.15	232823
Optimized correction	13.8	75.82	47.97	201213

We summarize the behavior of correction coefficients in Table 2 and show their characteristics with Figure 4. As presented in Table 2, the range of rainfall with 51-100 mm showed the highest number of AMS samples and had the most stable optimized coefficient (1.542). Rainfall classes above 100 mm, on the other hand, had extremely small sample sizes and their coefficients were substituted with a global value of 0.918. This pattern, which also appears in Figure 4, demonstrates that sample size had a strong control on coefficient stability. Thus, the piecewise correction was more reliable for the dominant middle rainfall class than it was for the extreme rainfall classes although these classes are most relevant to AMS-based analysis

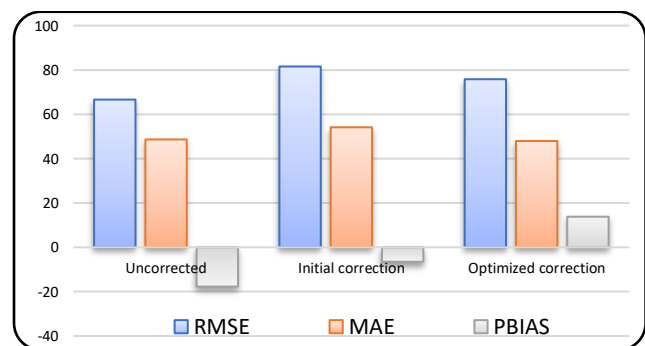


Figure 3. Performance metrics of GPM AMS correction scenarios

Table 2. Initial and optimized rainfall-range correction coefficients

Range (mm)	Initial Coef.	Optimal Coef.
0-5	0.000	0.000
6-15	0.800	0.800
16-25	0.900	0.900
26-50	0.950	0.950
51-100	1.050	1.542
101-125	1.125	0.918
126-150	1.250	0.918
>151	1.350	1.350

The accuracy of optimized correction without gauges was specified using leave-one-station-out validation, with outputs shown in Table 3 and plotted in Figure 5. Depending on which station was excluded, RMSE values ranged between 50.83 mm and 72.13 mm, as shown in Table 3. This can also be seen in Figure 4 where the highest value of RMSE was recorded for Taliwang whereas the lowest value belonged to Seteluk. These results suggest that the calibration was sensitive to station omission and that individual rain gauges exerted a strong influence on the optimum coefficients. However, the LOSO RMSE range identified in Table 3 and Figure 4 needs to be cautiously considered, given that the largest LOSO RMSE (72.13 mm) is lower than the optimized-correction RMSE stated in Table 1 (75.82 mm). Such discrepancies indicate that there are likely inconsistencies in the calculation basis/service set/evaluation framework between these two tables which should be cross-checked and clearly communicated

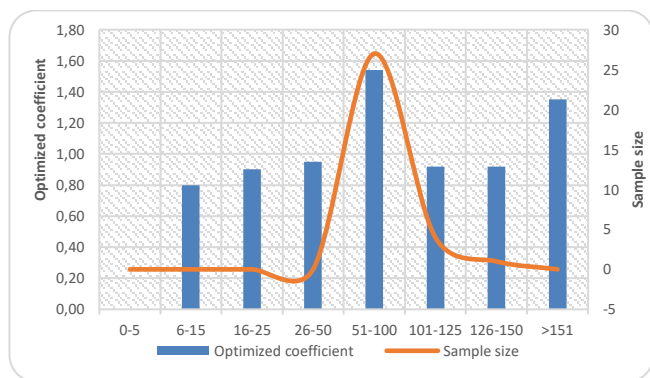


Figure 4. Optimized coefficients and sample size

Table 3. LOSO validation results for optimized correction

Exclude Site	PBIAS (%)	RMSE (mm)	MAE (mm)
Taliwang	14.8	72.13	55.96
Seteluk	20.9	50.83	36.65
Tepas	-8.10	61.65	45.94

The final correction coefficients applied to ungauged GPM grid cells are shown in Table 4 and Figure 6. As listed in Table 4, corrected AMS values ranged from 120 mm (GPM_2) to 150 mm (GPM_8) generally higher values were obtained for the upstream grids including GPM_6 (145 mm), GPM_8 (150 mm), and GPM_9 (148 mm). Figure 5 also depicts the same pattern visually. This upstream-downstream gradient is hydrologically reasonable because upper watershed areas are often linked with topographically lighter rainfalls. But this pattern cannot yet be claimed to be validated as the upstream area is not gauged and ground observations are lacking that would allow us to verify

whether higher values in Table 4 and Figure 5 were due to true rainfall conditions or residual satellite bias. Thus, the spatial results should be viewed as reasonable but imperfect estimates of progressive average annual maximum precipitation for the upstream Rea Watershed.

In general, results were synthesized from Tables 1-4 and Figs. 1-6 which indicated that the rainfall-range correction improved representation of systematic bias in GPM-derived rainfall estimates but did not enhance overall model performance compared to uncorrected data. The results showed that as shown in Table 1 and Figure 2, although the RMSE and SSE of the corrected products were lower than those of GPM L3 product (but still higher), it show that corrected product was not accurate. At the same time, in the highest rainfall classes, as seen from Table 2 and Figure 3, the correction coefficients were becoming unstable due to sample size being too low. Moderate robustness of the correction scheme across stations is also indicated in Table 3 and Figure 4, although its transferability remains limited. Ultimately, Table 5 and Figure 6 offer a plausible spatial pattern in the ungauged area but nothing yet that can be exhaustively evaluated. As such, the corrected GPM product is better interpreted as an initial bias-adjusted estimate for ungauged AMS assessment rather than a completely validated substitute to rain-gauge observations.

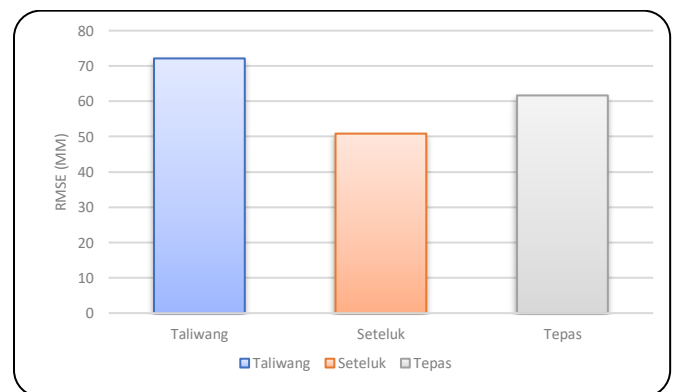


Figure 5. RMSE results of LOSO validation

Table 4. Corrected annual maximum daily rainfall (AMS) for GPM grids

GPM Grid	Location	Corrected AMS (mm)
GPM_4	Downstream	130
GPM_1	Middle	120
GPM_2	Middel	135
GPM_5	Middle	138
GPM_3	Upper	140
GPM_6	Upper	145
GPM_7	Upper	125
GPM_8	Upper	150
GPM_9	Upper	148

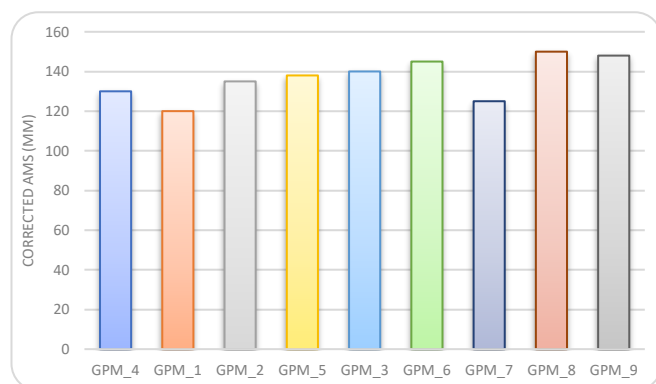


Figure 6. Corrected AMS across GPM grids

Conclusion

Therefore, this study aimed to investigate the effectiveness GPM satellite rainfall in estimating annual maximum daily rainfall for the Rea Watershed, especially ungauged upstream areas. Uncorrected GPM data tended to underpredict observed AMS rainfall in all tests. Even if the systematic bias was reduced in a local sense with this rainfall-range-based piecewise-approach, the overall predictability could not be improved which is shown by higher RMSE and SSE than for uncorrected output. This means that in general, the correction moved mean error values and not necessarily increased the precision of future extreme rainfall estimates.

Similarly, the results demonstrated that the piecewise correction relied heavily on sample availability considering every rainfall range. So coefficients were stable in classes for which there was enough data, but became biased/unreliable at higher rainfall ranges where most impact of AMS was concentrated. Moreover, the LOSO validation showed that although the correction results were sensitive to individual station exclusion, leading to limited consistency under sparse-gauge conditions. Corrected GPM data also resulted in increased AMS values upstream, although this spatial response could not be validated due to lack of ground observations in the ungauged headwater.

In conclusion, this study indicates an even greater promise for GPM satellite rainfall as a candidate information source addressing extreme rainfall uncertainty in data-sparse watersheds, yet the proposed piecewise linear correction is still not sufficient to produce consistently trustworthy AMS estimates at these time scales. As such, its use in hydrological design and flood-risk assessment must be approached with care and requires explicit treatment of uncertainty.

Future studies should cover longer rainfall records, and consider additional ground stations so that correction coefficients can remain sensitive for long

periods, in particular the extremes of high-rainfall. It would also be worthwhile to experiment with more flexible correction methods, including nonlinear, quantile-based, or topography-informed models to better represent the extreme rainfall behaviour during these events in our target ungauged mountainous areas. Moreover, calibrated satellite rainfall should be independently validated at up-enrain sites before it can be robustly applied for operational design and flood assessment.

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Author Contributions

Conceptualization, I.G.N.K.U. and H.S.; methodology, I.G.N.K.U., H.S. and H.; formal analysis, I.G.N.K.U. and H.S.; investigation, I.G.N.K.U.; resources, H.S. and H.; data curation, I.G.N.K.U.; writing—original draft preparation, I.G.N.K.U.; writing—review and editing, H.S. and H.; visualization, I.G.N.K.U.; supervision, H.S. and H.; project administration, H.; funding acquisition, H.S. and H. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest

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