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A Three-Parameter Aerosol Optical Discrimination Framework Integrating Fine-Mode Fraction, Single Scattering Albedo, and Differential Ångström Exponent over Selected AERONET Sites in Africa

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Abstract

Accurate aerosol optical discrimination remains challenging due to overlap among aerosol types under mixed atmospheric conditions. This study proposed a novel dAE-enhanced aerosol discrimination model using Fine Mode Fraction (FMF), Single Scattering Albedo (SSA), and Ångström Exponent Difference (dAE) derived from AERONET observations across African sites. Daily Level 2.0 aerosol retrievals were analyzed using FMF-SSA, FMF-dAE, and SSA-dAE relationships to evaluate the contribution of dAE in improving aerosol separation. Results showed that incorporation of dAE significantly reduced overlap between aerosol clusters and enhanced discrimination between fine-mode absorbing aerosols, mixed aerosols, and coarse mineral dust particles. Positive dAE values were associated with biomass burning and polluted continental aerosols, while near-zero or negative dAE values indicated coarse dust dominance. The proposed framework improves aerosol characterization and provides valuable applications for climate modeling, satellite validation, and radiative forcing assessment across Africa.

Keywords

Aerosol Discrimination, dAE, FMF, SSA, Africa

1. Introduction

Atmospheric aerosols significantly influence the Earth's climate system through their interactions with solar radiation, cloud microphysics, and atmospheric chemistry (Intergovernmental Panel on Climate Change (IPCC), 2021). Aerosol radiative effects remain one of the largest sources of uncertainty in climate forcing assessments because aerosol optical properties vary substantially across regions and source types (Zhang et al., 2025). Aerosols also affect visibility, precipitation processes, ecosystem productivity, and human health, particularly in regions characterized by intense biomass burning, dust outbreaks, and urban pollution (Ranaivombola et al., 2023; Situma et al., 2026).

Aerosol characterization commonly relies on optical parameters retrieved from ground-based remote sensing networks such as AERONET, which provides globally standardized observations of aerosol optical depth (AOD), Ångström Exponent (AE), Single Scattering Albedo (SSA), and Fine Mode Fraction (FMF) (Dubovik & King, 2000). These parameters are widely applied in aerosol discrimination studies because they provide indirect information on particle size distribution, scattering efficiency, and absorptive behavior (O'Neill et al., 2023). Among these parameters, FMF and SSA have become particularly useful in identifying dominant aerosol regimes including mineral dust, biomass burning aerosols, urban-industrial pollution, and marine aerosols (Chen et al., 2024).

Despite the success of FMF-SSA classification approaches, substantial overlap often exists between aerosol populations under mixed atmospheric conditions (Mishra et al., 2024). Similar FMF-SSA combinations may represent entirely different aerosol mixtures, thereby limiting the reliability of traditional two-parameter discrimination models (Giannakaki et al., 2023). This limitation is especially evident in Africa, where multiple aerosol sources coexist and interact seasonally across large spatial scales (Ranaivombola et al., 2023).

Northern Africa is strongly dominated by coarse mineral dust aerosols originating from the Sahara Desert, whereas Southern Africa experiences substantial contributions from biomass burning emissions and polluted continental aerosols (Formenti et al., 2018). These aerosol systems frequently mix during long-range transport, creating transitional aerosol states that are difficult to distinguish using conventional optical discrimination methods (Ranaivombola et al., 2023; Chen et al., 2024). Consequently, there is increasing interest in developing enhanced aerosol discrimination frameworks capable of resolving aerosol mixtures with greater precision (Mishra et al., 2024).

Recent aerosol studies have emphasized the importance of incorporating spectral curvature information into aerosol classification models because conventional AE alone may not adequately capture aerosol size heterogeneity (Ranaivombola et al., 2023; Zhang et al., 2025). The Ångström Exponent Difference (dAE), defined as the difference between AE calculated over two wavelength intervals, provides additional sensitivity to spectral variations associated with mixed aerosol populations (O'Neill et al., 2023). Positive dAE values are generally linked to fine-mode aerosol dominance, whereas negative or near-zero values indicate coarse-mode particle influence (Formenti et al., 2018).

Over Africa, several studies have demonstrated the effectiveness of AERONET-derived optical properties for aerosol source identification and characterization. For instance, strong seasonal variations in aerosol optical properties over East Africa associated with biomass burning, urban emissions, and long-range transported dust have been observed (Khamala et al., 2023). Similarly, the influence of regional transport processes and mixed aerosol conditions on aerosol optical characteristics across African environments has been highlighted, which has emphasized the importance of advanced aerosol discrimination approaches for improving aerosol source attribution and climate impact assessments over the continent (Khamala et al., 2023; Situma et al., 2026).

Although dAE has demonstrated potential for representing aerosol spectral behavior, its integration into aerosol optical discrimination models remains limited, particularly over Africa, where aerosol mixing processes are highly dynamic (Ranaivombola et al., 2023). Incorporating dAE into FMF-SSA space may therefore improve separation among aerosol clusters and reduce ambiguity associated with overlapping aerosol regimes (Chen et al., 2024).

This study proposes a novel dAE-enhanced aerosol optical discrimination model based on FMF, SSA, and dAE derived from AERONET observations across African sites. The study investigates how dAE improves aerosol discrimination within FMF-SSA space and evaluates regional aerosol variability between North and South Africa. The proposed framework aims to enhance aerosol typing capability for climate studies, satellite validation, and radiative forcing assessments (Zhang et al., 2025).

2. Study Area, Data, and Methods

2.1. Study Area and Data Source

This study utilized aerosol optical observations obtained from selected African Aerosol Robotic Network (AERONET) stations representing contrasting aerosol environments across North and South Africa (**Figure 1**). The selected twelve AERONET sites capture dominant regional aerosol regimes, including Saharan dust, biomass burning smoke, marine aerosols, and polluted continental particles. Grouping the stations into North and South African regions enabled assessment of regional aerosol variability associated with different emission sources and atmospheric transport processes.

AERONET Version 3 Level 2.0 quality-assured daily averaged retrievals were used in this study because they provide cloud-screened and calibration-corrected aerosol optical parameters with improved uncertainty characterization (Boiyo et al., 2017; Giles et al., 2019). Daily averages were selected to minimize short-term fluctuations while preserving synoptic aerosol variability relevant for aerosol discrimination analysis (O'Neill et al., 2023).

2.2. Aerosol Discrimination Framework

The aerosol discrimination framework was developed using three complementary parameter relationships: FMF-SSA, FMF-dAE, and SSA-dAE (Mishra et al., 2024).

In the FMF-SSA analysis, dAE was incorporated as a color-coded parameter to visualize spectral variability within conventional aerosol discrimination space (Chen et al., 2024). This approach enabled the identification of hidden aerosol transitions and mixed aerosol regimes that may not be clearly resolved using FMF and SSA alone (Zhang et al., 2025).

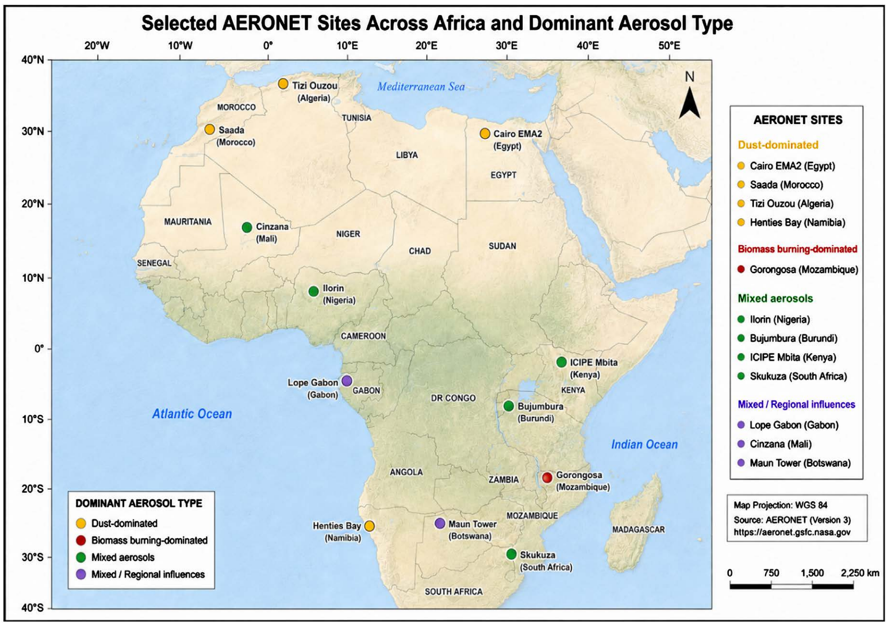

Figure 1. Spatial distribution of selected AERONET version 3 sites across Africa and their dominant aerosol types, classified as dust-dominated, biomass burning-dominated, mixed aerosols, and mixed/regional influences, illustrating the regional variability of aerosol sources and atmospheric transport processes over the continent.

Scatter distributions were analyzed to identify aerosol clustering behavior associated with dominant aerosol types across Africa. Fine-mode absorbing aerosols such as biomass burning smoke were expected to exhibit high FMF and lower SSA values, whereas coarse mineral dust aerosols were expected to occupy lower FMF regions with variable SSA characteristics (Formenti et al., 2018).

2.3. Statistical Analysis

The conventional aerosol classification framework is based on the joint relationship between the Fine Mode Fraction (FMF) and Single Scattering Albedo (SSA), where FMF represents particle size dominance, and SSA characterizes aerosol absorptive properties (**Table 1**) (Giles et al., 2019; Khamala et al., 2023).

Table 1. Statistical and analytical framework applied in the study.

Analysis Component	Method Applied	Purpose
Data Source	AERONET Version 3 Level 2.0	Obtain quality-assured aerosol optical properties

Continued

Temporal Resolution	Daily averages	Reduce short-term variability
Aerosol Parameters	FMF, SSA, AE, dAE	Characterize aerosol optical behavior
dAE Computation	AE440-675-AE675-870	Quantify aerosol spectral curvature
Scatter Analysis	FMF-SSA, FMF-dAE, SSA-dAE	Evaluate aerosol clustering behavior
Regional Comparison	North vs South Africa	Assess regional aerosol variability
Aerosol Interpretation	Threshold-based optical classification	Identify dominant aerosol regimes

The primary framework was expressed as:

$$F_1 = f\left(FMF, SSA\right) \tag{1}$$

where F_1 denotes the conventional two-parameter aerosol discrimination space.

The Fine Mode Fraction (FMF) is defined as the proportion of aerosol optical depth (AOD) contributed by fine particles:

$$FMF = \frac{AOD_{fine}}{AOD_{total}} \tag{2}$$

With values approaching unity indicating fine-particle dominance and lower values indicating coarse-mode aerosols (Khamala et al., 2023).

The Single Scattering Albedo (SSA) is defined as:

$$SSA = \frac{\sigma_{sca}}{\sigma_{sca} + \sigma_{abs}} \tag{3}$$

where σ_{sca} and σ_{abs} are the aerosol scattering and absorption coefficients, respectively, lower SSA values indicate stronger aerosol absorption, while higher values correspond to predominantly scattering particles (Boiyo et al., 2017).

To improve discrimination between aerosol types exhibiting similar FMF-SSA characteristics but different spectral behaviors, this study introduced the differential Ångström Exponent (dAE) as an additional constraint. The dAE was computed as:

$$dAE = AE_{440\text{-}675nm} - AE_{675\text{-}870nm} \tag{4}$$

where $AE_{440\text{-}675\mathrm{nm}}$ and $AE_{675\text{-}870\mathrm{nm}}$ are Ångström exponents calculated over the respective wavelength intervals. The parameter quantified spectral curvature and provided information on particle-size distribution and aerosol modification processes that may not be evident from FMF or SSA alone (Holben et al., 1998). The proposed enhanced framework, therefore, extended the conventional two-dimensional classification to:

$$F_2 = f\left(FMF, SSA, dAE\right) \tag{5}$$

where F_2 represented the novel three-parameter aerosol discrimination space adopted in this study.

For each collocated daily observation, the aerosol feature vector was expressed as:

$$x_i = \left[FMF_i, SSA_i, dAE_i \right] \tag{6}$$

allowing simultaneous assessment of particle-size dominance, radiative characteristics, and spectral variability.

Scatter-distribution analysis was then performed in the FMF-SSA and FMF-SSA-dAE parameter spaces to identify aerosol clusters and evaluate the additional discriminatory capability provided by dAE. Correlation analyses were further used to assess relationships among the variables and infer aerosol mixing and aging processes. Regional comparisons between northern and southern African observation sites were conducted to evaluate differences in aerosol composition, transport, and spectral variability associated with contrasting atmospheric environments. The spatial patterns of the resulting clusters were interpreted in the context of dominant regional emission sources and long-range transport mechanisms (Ranaivombola et al., 2023; Mishra et al., 2024; Zhang et al., 2025).

3. Results and Discussion

3.1. Trend in Aerosol Optical Depth (AOD)

Figure 2 presents the relationship between FMF and SSA, with dAE represented as a color gradient. The distribution reveals considerable overlap among aerosol populations when only FMF and SSA are considered, confirming limitations previously reported in conventional aerosol discrimination frameworks (Mishra et al., 2024). However, incorporation of dAE introduces additional spectral information that improves separation among aerosol clusters (Dubovik et al., 2002; O'Neill et al., 2003; Situma et al., 2026).

Higher dAE values were predominantly associated with elevated FMF and moderate SSA conditions, indicating dominance of fine-mode aerosols characterized by strong spectral curvature (O'Neill et al., 2023) (**Table 2**). These aerosol characteristics are consistent with biomass burning and polluted continental aerosols commonly observed over Southern Africa during intense fire seasons (Ranaivombola et al., 2023; Situma et al., 2026). Conversely, lower or negative dAE values were concentrated under lower FMF conditions, reflecting dominance of coarse mineral dust aerosols typically transported from the Sahara Desert (**Table 3**) (Giannakaki et al., 2023).

The distribution pattern demonstrates that dAE effectively constrains aerosol size heterogeneity within FMF-SSA space and therefore reduces ambiguity associated with overlapping aerosol regimes (Zhang et al., 2025). This enhanced discrimination capability is particularly important for African aerosol environments where aerosol mixing processes are highly dynamic and spatially heterogeneous (Formenti et al., 2018; Situma et al., 2026).

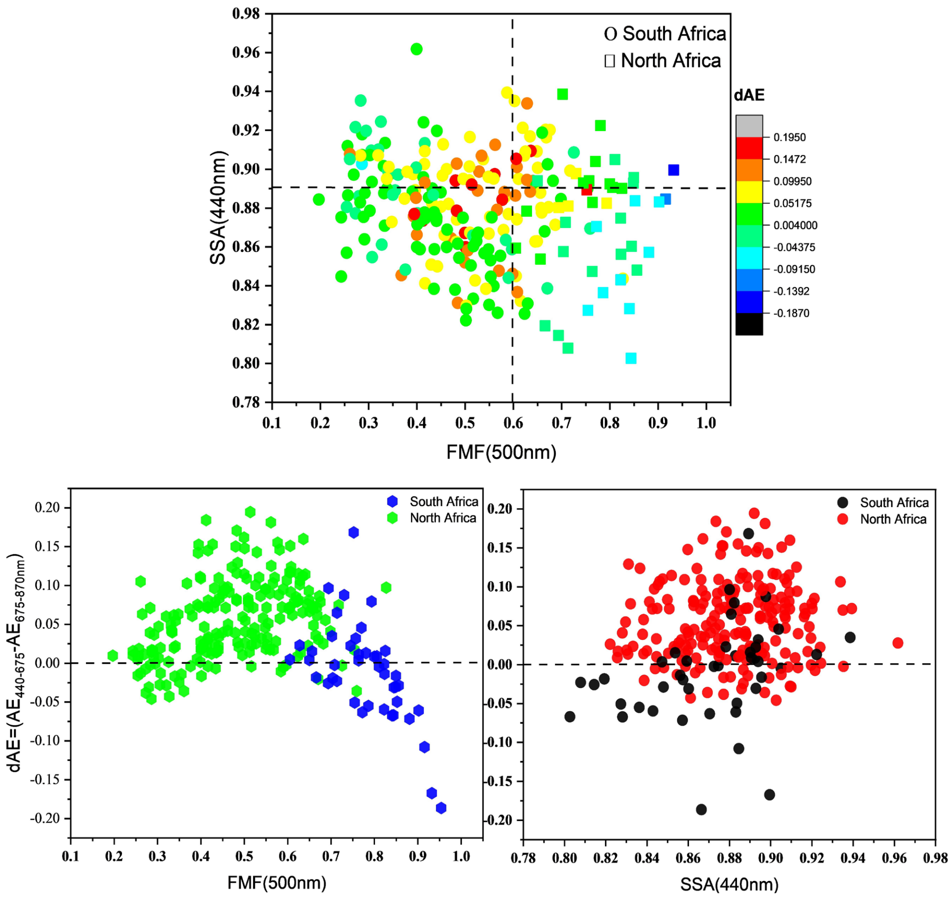

Figure 2. Relationships between FMF (500 nm), SSA (440 nm), and dAE ($AE_{440\text{-}675}$-$AE_{675\text{-}870\text{nm}}$) across African AERONET sites: (a) FMF-SSA (colored by dAE; dashed lines at FMF = 0.6 and SSA = 0.89), (b) FMF-dAE (dAE = 0 shown), and (c) SSA-dAE. Data are grouped into North and South Africa.

Table 2. Interpretation of scatterplot relationships in the dAE-enhanced aerosol discrimination model.

Scatter Relationship	Major Observation	Aerosol Implication	Interpretation
FMF-SSA	Significant overlap among aerosol clusters	Conventional discrimination limitation	Aerosol mixtures are difficult to separate using two parameters alone
FMF-SSA-dAE	Improved cluster separation after inclusion of dAE	Enhanced aerosol discrimination	dAE introduces sensitivity to spectral curvature
FMF-dAE	Positive relationship between FMF and dAE	Fine-mode aerosol dominance	Biomass burning and polluted aerosols exhibit stronger spectral curvature
SSA-dAE	Lower SSA associated with positive dAE	Absorbing aerosol behavior	Biomass burning aerosols dominate absorbing clusters
Transitional Clusters	Intermediate dAE and FMF values	Mixed aerosol conditions	Indicates aerosol mixing and long-range transport

Table 3. Regional aerosol characteristics across Africa.

Region	Dominant Aerosol Type	FMF Behavior	SSA Behavior	dAE Behavior	Dominant Atmospheric Processes
North Africa	Mineral Dust	Low FMF	Moderate SSA	Negative to near-zero dAE	Saharan dust transport
South Africa	Biomass Burning /Polluted Continental	High FMF	Lower SSA	Positive dAE	Biomass burning emissions
Transitional Regions	Mixed Aerosols	Moderate FMF	Variable SSA	Transitional dAE	Dust-smoke interactions

3.2. FMF-dAE Relationship

A clear positive relationship exists between the two parameters, indicating increasing spectral curvature with increasing fine-mode aerosol contribution (**Figure 2**). Fine-mode aerosols exhibited predominantly positive dAE values, reflecting stronger wavelength dependence associated with combustion-generated particles and secondary aerosols (Chen et al., 2024).

Coarse-mode aerosols clustered near or below dAE = 0, consistent with weaker spectral variation typically associated with mineral dust particles (**Figure 1**) (Giannakaki et al., 2023). The clearer separation observed in FMF-dAE space compared to FMF-SSA space demonstrated the sensitivity of dAE to aerosol size transitions and mixed aerosol conditions (**Tables 2-4**) (Zhang et al., 2025; Situma et al., 2026).

Table 4. Proposed aerosol classification characteristics in the dAE-enhanced framework.

Aerosol Type	FMF Characteristics	SSA Characteristics	dAE Characteristics	Dominant Aerosol Sources
Mineral Dust (DU)	Low FMF	Moderate to high SSA	Negative or near-zero dAE	Saharan desert dust
Biomass Burning (BB)	High FMF	Low SSA	Positive dAE	Vegetation fires and smoke
Polluted Continental (PC)	High FMF	Moderate SSA	Positive dAE	Urban-industrial emissions
Mixed Aerosols (MXD)	Moderate FMF	Variable SSA	Transitional dAE values	Dust-smoke-pollution mixtures
Marine Aerosols (MAR)	Low to moderate FMF	High SSA	Near-zero dAE	Sea salt and oceanic particles

Several transitional data points were observed between the dominant clusters, indicating coexistence of fine and coarse aerosol populations under mixed atmospheric conditions (Mishra et al., 2024). Such mixed aerosol states are common over Africa due to interactions between transported Saharan dust, biomass burning smoke, and urban-industrial emissions (Formenti et al., 2018). The observed transitional structures further confirm the usefulness of dAE in identifying aerosol mixing processes that are not adequately resolved using conventional aerosol optical parameters alone (Ranaivombola et al., 2023).

3.3. SSA-dAE Relationship

Analysis of the relationship between SSA and dAE revealed lower SSA values, primarily associated with positive dAE values, indicating absorbing fine-mode aerosols dominated by biomass burning smoke and black carbon-rich particles (**Figure 2**) (Zhang et al., 2025). These aerosols are known to exhibit enhanced absorption and strong spectral curvature due to their small particle sizes and combustion origin (Chen et al., 2024; Situma et al., 2026).

Higher SSA values displayed broader dAE variability, reflecting mixtures of scattering and absorbing aerosol components under varying atmospheric conditions (Mishra et al., 2024). The relatively compact clustering observed for absorbing aerosols suggested that dAE improves the identification of combustion-related aerosol populations that are often poorly separated using SSA alone (**Table 5**).

Table 5. Advantages of the proposed dAE-enhanced aerosol discrimination model.

Conventional FMF-SSA Model Limitation	Contribution of dAE	Improvement Achieved
Overlapping aerosol clusters	Introduces spectral curvature sensitivity	Improved aerosol separation
Poor identification of mixed aerosols	Captures aerosol size heterogeneity	Better mixed aerosol detection
Limited sensitivity to aerosol transitions	Resolves fine-to-coarse particle variability	Enhanced transitional aerosol characterization
Ambiguity in absorbing aerosol classification	Links absorption to spectral behavior	Improved biomass burning aerosol identification
Reduced regional discrimination capability	Enhances spectral differentiation	Better regional aerosol interpretation across Africa

Regional contrasts were also evident within the SSA-dAE relationship. Southern African sites exhibited stronger fine-mode absorbing signatures associated with seasonal biomass burning emissions, whereas North African stations displayed broader coarse-mode variability linked to Saharan dust transport (**Table 4**) (Formenti et al., 2018). These findings demonstrated that dAE provides additional discriminatory power for interpreting aerosol absorptive behavior and aerosol source characteristics across Africa (Giannakaki et al., 2023).

3.4. Implications of the dAE-Enhanced Aerosol Discrimination Model

The proposed dAE-enhanced aerosol discrimination model demonstrates improved capability in resolving aerosol mixtures compared to conventional two-parameter approaches (Table 5).

Incorporation of dAE introduces sensitivity to spectral curvature and aerosol size transitions, thereby enhancing aerosol cluster separation and reducing classification ambiguity. The improved aerosol discrimination achieved in this study has important implications for satellite aerosol retrieval validation, climate modeling, radiative forcing estimation, and air quality assessment (Mishra et al., 2024). Enhanced aerosol typing frameworks are particularly valuable over Africa, where aerosol complexity and limited observational coverage continue to challenge atmospheric modeling efforts (Ranaivombola et al., 2023).

4. Summary and Conclusion

This study developed a novel dAE-enhanced aerosol optical discrimination model using FMF, SSA, and dAE derived from AERONET observations across African sites. The results demonstrate that incorporation of dAE significantly improves aerosol separation within conventional FMF-SSA space by introducing sensitivity to spectral curvature and aerosol size heterogeneity. The FMF-dAE relationship revealed clear separation between fine-mode and coarse-mode aerosol populations, while the SSA-dAE relationship improved identification of absorbing aerosol regimes associated with biomass burning emissions. Regional analysis further highlighted strong contrasts between North African dust-dominated environments and Southern African biomass burning aerosol regimes.

Looking at it as a whole, the findings confirmed that dAE is a valuable supplementary parameter for aerosol optical discrimination and substantially enhances characterization of mixed aerosol environments over Africa. The proposed framework has provided a promising basis for future aerosol classification studies, satellite retrieval improvement, and aerosol radiative forcing assessments under complex atmospheric conditions.

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Author Contributions

Situma Yonah: conceptualization, data curation, formal analysis, methodology, visualization, and writing original draft. **Makokha John:** supervision, methodology, validation, review, and editing. **Khakina Peter:** data curation, formal analysis, investigation, and validation. **Khamala Geoffrey:** data curation, formal analysis, investigation, review, and editing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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