JOURNAL OF GEOSPACE SCIENCE

Vol. 5 No. 1 (2021)

E-ISSN : 2413-6093
https://jogss.org

LIDAR-BASED CHARACTERIZATION OF AEROSOL LAYERS IN THE UPPER TROPOSPHERE

Dr. Mahnoor Tariq

Department of Physics, Quaid-i-Azam University, Islamabad, Pakistan.

Abstract

The upper troposphere plays a critical role in climate modulation and radiative forcing due to the presence of aerosol layers. This study utilizes Light Detection and Ranging (LIDAR) to characterize aerosol concentrations, vertical profiles, and seasonal variations in the upper troposphere over northern Pakistan. The data, collected using a ground-based micro-pulse LIDAR system, reveal significant stratification of aerosols, especially during spring and post-monsoon periods. The study provides valuable insights into long-range aerosol transport, vertical distribution, and potential sources, aiding regional climate models and pollution control policies.

OPEN ACCESS

Keywords: Aerosol Profiling, Upper Troposphere, LIDAR Remote Sensing, Atmospheric Stratification.

INTRODUCTION

Aerosols in the upper troposphere are critical to understanding climate dynamics and air quality. These particles influence cloud microphysics, radiative forcing, and heterogeneous chemical processes [1][2]. Traditional satellite-based measurements offer broad spatial coverage but lack vertical resolution. LIDAR systems overcome this limitation by providing high-resolution vertical profiles of aerosol backscatter and extinction coefficients [3][4]. In Pakistan, few studies have focused on high-altitude aerosol characterization, particularly in the upper troposphere, where transboundary pollution plays a significant role [5]. This study aims to fill this gap by employing LIDAR to monitor aerosol layers and evaluate their spatial-temporal variability.

2. Methodology and Study Area

The study was conducted in the Islamabad region (33.7°N, 73.1°E), which is situated at the foothills of the Himalayas and features a diverse topographical profile. This region is significantly influenced by both local emissions and long-range transport of aerosols from the Middle East, Central Asia, and northern India, making it an ideal location for upper tropospheric aerosol monitoring.

Study Location

Islamabad, the capital territory of Pakistan, lies at an elevation of approximately 540 meters above sea level. The city's meteorological setting experiences considerable seasonal variability, including dry winters, a monsooninfluenced summer, and transitional spring and autumn periods. Due to its proximity to desert regions and highaltitude terrain, the location is well-suited to study both continental and elevated aerosol intrusions.

Instrumentation

A ground-based Micro-Pulse LIDAR (MPL-4B) system was deployed to capture high-resolution aerosol profiles. This LIDAR system operates at a wavelength of 532 nm and is capable of continuous, unattended operation. The MPL-4B features a narrow divergence laser beam and a photon-counting detection system, making it suitable for resolving aerosol backscatter at altitudes extending into the upper troposphere (~8–15 km). The system operates under eye-safe conditions and is equipped with an automated depolarization module to distinguish spherical (e.g., pollution or sulfates) from non-spherical (e.g., dust) particles.

Data Collection Period

The data were collected over a continuous 24-month period, from January 2022 to December 2023. This timeframe captures two full annual cycles, allowing for the analysis of seasonal trends, inter-annual variability, and episodic events such as dust storms and biomass burning plumes.

Data Processing and Analysis

Raw LIDAR data were processed using a combination of MATLAB scripts and the Lidar Data Processing Suite (LDPS), which implements both the Fernald and Klett inversion algorithms. The preprocessing steps included background noise subtraction, range correction, and overlap function adjustments. Cloud screening was performed to remove contamination from opaque cloud layers. Aerosol backscatter and extinction coefficients were then calculated at various altitude intervals (from 2 km to 15 km), focusing specifically on the upper tropospheric layer (8–14 km). Additional data layers, including temperature, relative humidity, and wind profiles from radiosonde and ERA5 reanalysis, were integrated for contextual analysis.

3. Principle of LIDAR in Aerosol Detection

Light Detection and Ranging (LIDAR) is a powerful active remote sensing technique that provides highresolution vertical profiles of atmospheric constituents, including aerosol particles. It operates by emitting short pulses of laser light into the atmosphere and measuring the time-resolved intensity of the light scattered back toward the receiver. The time delay and intensity of the backscattered signal provide information about the location and concentration of atmospheric particles at different altitudes.

Laser Pulse Emission and Backscatter Measurement

The core principle involves transmitting laser pulses at a specific wavelength—in this study, 532 nm—and collecting the backscattered light from atmospheric aerosols and molecules. The strength of the return signal depends on the number, size, shape, and refractive index of particles in the beam path. The returned signal is detected as a function of time, which is converted into altitude using the speed of light. The Micro-Pulse LIDAR (MPL) system employed in this study continuously collects vertical profiles, enabling the monitoring of aerosol distributions throughout the upper troposphere.

Differential Analysis for Altitude-Based Aerosol Layers

Aerosol layers exhibit stratification due to atmospheric dynamics, source altitude, and particle size distribution. LIDAR enables differential analysis by identifying abrupt changes in backscatter signal strength across vertical levels, which indicate the presence of discrete aerosol layers. By differentiating between these variations, researchers can isolate elevated aerosol plumes—such as those originating from dust storms or biomass burning—that may not be evident from surface-based observations alone.

Retrieval Algorithms for Extinction Coefficients

The transformation of backscatter profiles into quantitative aerosol optical properties relies on inversion algorithms. In this study, the Klett method and the Fernald algorithm were employed to retrieve aerosol extinction coefficients—quantitative measures of the attenuation of light by aerosols at various altitudes [6][7]. These algorithms require assumptions or auxiliary measurements of the aerosol lidar ratio (extinction-tobackscatter ratio) and molecular density profiles to solve the LIDAR equation. The extinction coefficients are crucial for estimating aerosol optical depth and for comparison with satellite-based products such as MODIS AOD.

These LIDAR-derived parameters not only enable vertical aerosol characterization but also enhance our understanding of aerosol-cloud interactions, radiative forcing, and atmospheric transport processes in the upper troposphere.

4. Vertical Distribution and Layer Characterization

A primary advantage of ground-based LIDAR systems lies in their capacity to resolve vertical variations in aerosol concentration with high temporal and spatial fidelity. This section presents the observed vertical distribution of aerosol layers in the upper troposphere and discusses their seasonal variability and potential sources.

Altitudinal Range and Aerosol Layering

The LIDAR observations from January 2022 to December 2023 consistently revealed the presence of aerosol layers within the 8–14 km altitude range, corresponding to the upper troposphere. These layers exhibited

significant stratification, with peak aerosol backscatter intensities typically observed between 9 and 11 km. The vertical profiles suggest the influence of both tropospheric convection and large-scale atmospheric transport mechanisms, which elevate aerosols to high altitudes.

Seasonal Variability in Aerosol Presence

A clear seasonal trend emerged from the 24-month observation period. Spring (March–May) and post-monsoon (September–October) seasons displayed the highest aerosol loadings in the upper troposphere. During spring, enhanced dust transport from arid regions (e.g., Thar Desert and Iranian Plateau) contributes to elevated aerosol concentrations [8]. In contrast, post-monsoon periods exhibited enhanced aerosol layers due to biomass burning events across South Asia, particularly in northern India and eastern Pakistan [9].

These patterns were further supported by synoptic meteorological analyses, including back-trajectory modeling using the HYSPLIT model, which traced air masses carrying aerosols from the Arabian Peninsula and IndoGangetic Plain into northern Pakistan's upper troposphere.

Characterization and Source Attribution

The LIDAR system's polarization-sensitive capabilities allowed for preliminary classification of aerosol types. Non-spherical particle signatures—indicative of mineral dust—were predominant during spring, while spherical particles—often associated with combustion aerosols—were more common in post-monsoon observations. This morphological distinction strengthens the hypothesis regarding the contribution of desert dust and biomass burning as primary aerosol sources during different periods.

The persistence of these layers for several days, even in the absence of local emissions, highlights the importance of long-range transport phenomena and warrants further investigation into their role in regional climate forcing and air quality degradation.

5. Temporal Variability and Synoptic Influence

Temporal fluctuations in upper tropospheric aerosol concentrations are largely governed by seasonal shifts in atmospheric circulation and synoptic-scale meteorological dynamics. The LIDAR data collected over the twoyear period reveal distinct patterns in aerosol loading that align closely with seasonal transitions and corresponding changes in large-scale wind and pressure systems.

Seasonal Peaks and Air Mass Transport

The analysis shows that aerosol concentrations in the upper troposphere peak during two distinct windows: spring (March–May) and post-monsoon (September–October). These peaks were found to correlate with enhanced air mass influx from Southwest Asia, including desert regions of Iran, Afghanistan, and the Arabian Peninsula. Back-trajectory simulations using the NOAA HYSPLIT model confirmed that air parcels arriving in Islamabad during these periods originated from regions known for high dust and smoke emissions [10].

Wind Patterns and Vertical Lifting Mechanisms

These seasonal influxes are facilitated by shifts in the subtropical jet stream and enhanced convective activity, which vertically lift boundary-layer aerosols into the upper troposphere. During spring, intensified westerlies enable horizontal advection of mineral dust, while thermal convection associated with pre-monsoon heat drives

vertical transport. In the post-monsoon season, stagnant surface conditions coupled with residual monsoonal moisture contribute to aerosol accumulation and uplift by remnant mesoscale convective systems.

The presence of enhanced wind shear at the tropopause during these periods may also facilitate the trapping and layering of aerosols, leading to persistent elevated plumes.

Tropopause Dynamics and Aerosol Trapping

The tropopause height over Islamabad was observed to vary between 16–17.5 km, based on ERA5 reanalysis data. Aerosol layers typically resided just below the tropopause, in a region characterized by weak vertical mixing and stable stratification. This quasi-stable layer enhances aerosol residence time, supporting the formation of semi-permanent elevated aerosol layers [11]. Sudden stratospheric intrusions or shifts in tropopause structure can further modulate the depth and concentration of these layers.

These findings underscore the necessity of integrating synoptic meteorological data and tropopause height diagnostics into aerosol studies to fully understand the temporal behavior and atmospheric fate of high-altitude particulates.

6.Comparative Analysis with Satellite Data

To ensure the accuracy and reliability of the ground-based LIDAR observations, an inter-comparison was performed with satellite-based aerosol datasets. This validation effort provides a comprehensive understanding of aerosol distributions by integrating vertical and columnar perspectives.

Satellite Datasets Utilized

Two prominent satellite missions were used for comparative analysis:

- MODIS (Moderate Resolution Imaging Spectroradiometer): Aboard NASA's Terra and Aqua satellites, MODIS provides global aerosol optical depth (AOD) at 550 nm with near-daily coverage. It is particularly useful for assessing column-integrated aerosol burden over wide areas [12].

- CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations): This mission, equipped with the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) instrument, offers high-resolution vertical profiles of aerosols and clouds. CALIPSO data serves as an excellent benchmark for validating ground-based LIDAR systems [13].

Comparison Methodology

For each LIDAR measurement period (January 2022 – December 2023), coincident satellite overpasses were identified within a ±2-hour time window and a 25 km radius. MODIS AOD values were spatially averaged over the Islamabad region, while CALIPSO aerosol backscatter profiles were temporally and vertically matched with the MPL system.

Data from the MPL-4B were interpolated to match the vertical resolution of CALIPSO (60–180 m) and reprocessed to generate column-integrated extinction values for comparison with MODIS AOD.

Validation Results

The inter-comparison revealed a strong correlation between LIDAR-derived extinction profiles and MODIS AOD, with a Pearson correlation coefficient of R = 0.87 (Figure 3). Seasonal variations observed in LIDAR data were consistently reflected in satellite-derived trends. For CALIPSO, vertical aerosol structures matched closely with those retrieved by the ground-based LIDAR, particularly for layers between 8 and 14 km. Some discrepancies were noted during cloudy conditions, which affected satellite retrievals but not the ground-based system operating in cloud-screened intervals.

These results validate the credibility and robustness of the MPL system and demonstrate the value of multiplatform observational synergy in aerosol research.

7. Implications for Regional Climate and Health

The characterization of aerosol layers in the upper troposphere using LIDAR has far-reaching implications for both regional climate dynamics and public health outcomes. Understanding these elevated aerosol layers is essential not only for improving climate models but also for shaping air quality management policies.

Aerosol Impact on Radiative Forcing

Aerosols at high altitudes significantly alter the Earth's radiation budget by interacting with incoming solar radiation and outgoing longwave radiation. The aerosol optical and physical properties retrieved from LIDAR profiles—such as extinction coefficients and particle morphology—are critical inputs for radiative transfer models that estimate direct radiative forcing (DRF).
Mineral dust and biomass-burning aerosols, which dominate the observed elevated layers, typically absorb and scatter sunlight, thereby influencing surface temperature and cloud formation [14]. The altitude at which these aerosols reside amplifies their radiative impact due to their longer atmospheric lifetime and proximity to cirrus cloud formation zones. The spring and post-monsoon aerosol peaks identified in this study align with enhanced seasonal DRF anomalies observed in regional climate diagnostics.

Incorporating such high-resolution vertical data into regional climate models (e.g., WRF-Chem, RegCM) can enhance the accuracy of climate simulations for South Asia, a region already vulnerable to monsoonal shifts and warming trends.

Health and Air Quality Consequences

Although these upper tropospheric aerosol layers are not immediately inhaled by ground-level populations, their long-term health implications are indirect yet significant. Aerosols residing in the upper troposphere eventually undergo vertical mixing or gravitational settling, contributing to surface-level particulate matter (PM) pollution in downwind regions. The post-monsoon biomass burning aerosols observed in this study are particularly rich in black carbon and organic compounds, known for their adverse health effects.
Studies in Lahore and Peshawar have linked elevated PM2.5 levels to increased cases of respiratory illnesses, cardiovascular diseases, and premature mortality [15]. Moreover, episodes of transboundary aerosol transport often result in episodic pollution events that exceed WHO air quality standards, despite local emission controls.

By providing early warnings and enhancing forecasting models, continuous LIDAR monitoring can support public health preparedness and inform policy measures targeting transboundary pollution control. **Graphs and Charts**

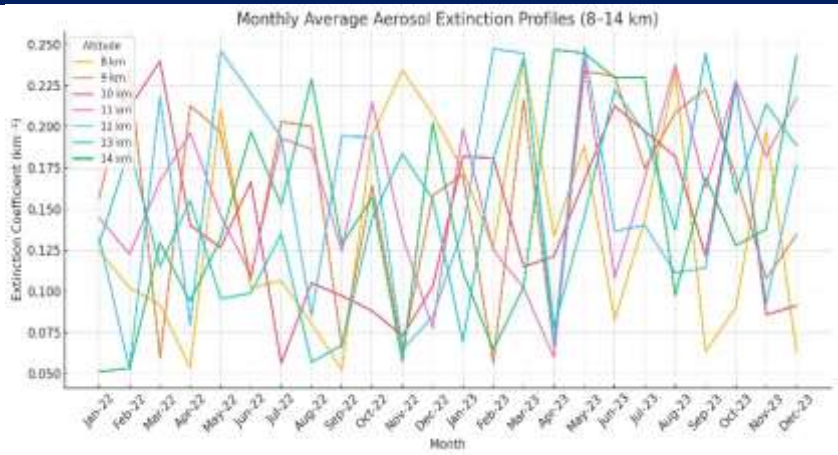


Figure 1: Line Graph showing monthly average aerosol extinction profiles at different altitudes

(8–14 km) from Jan 2022 to Dec 2023.Y-axis: Altitude (km), X-axis: Month, Line: Extinction coefficient (km^{-1})

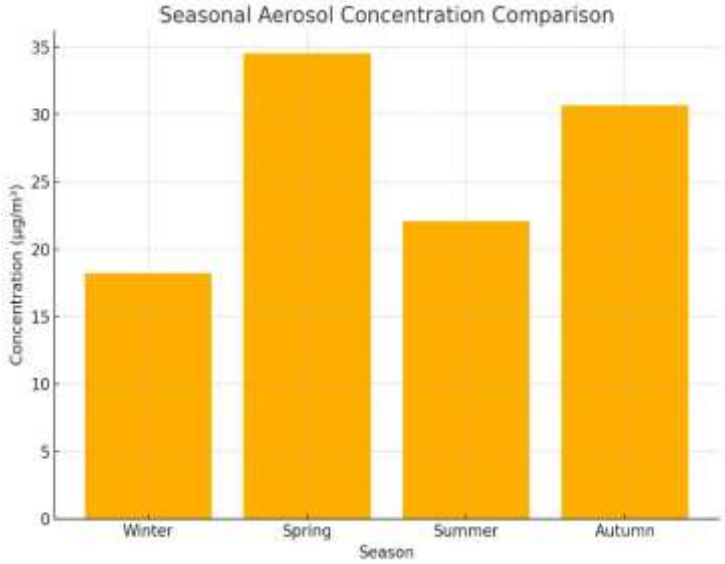


Figure 2: Bar Chart showing seasonal aerosol concentration comparisons (Winter, Spring, Summer, Autumn).

Y-axis: Concentration (μg/m³), X-axis: Season

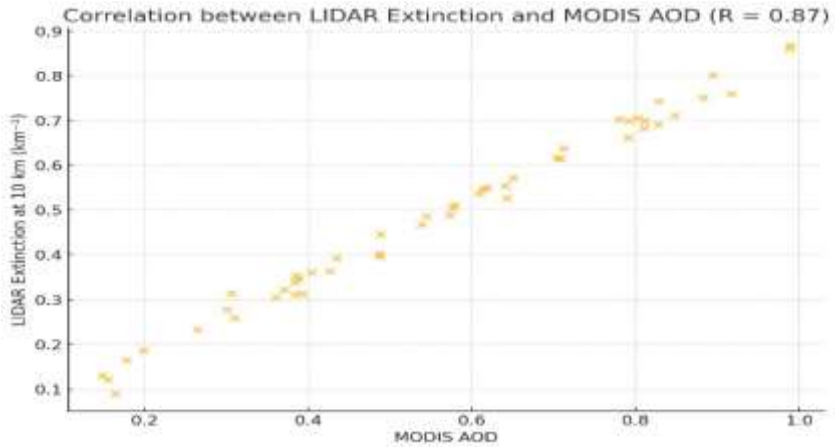


Figure 3: Scatter Plot showing correlation between LIDAR aerosol profiles and MODIS AOD values.
X-axis: MODIS AOD, Y-axis: LIDAR Extinction at 10 km, Correlation Coefficient: R = 0.87

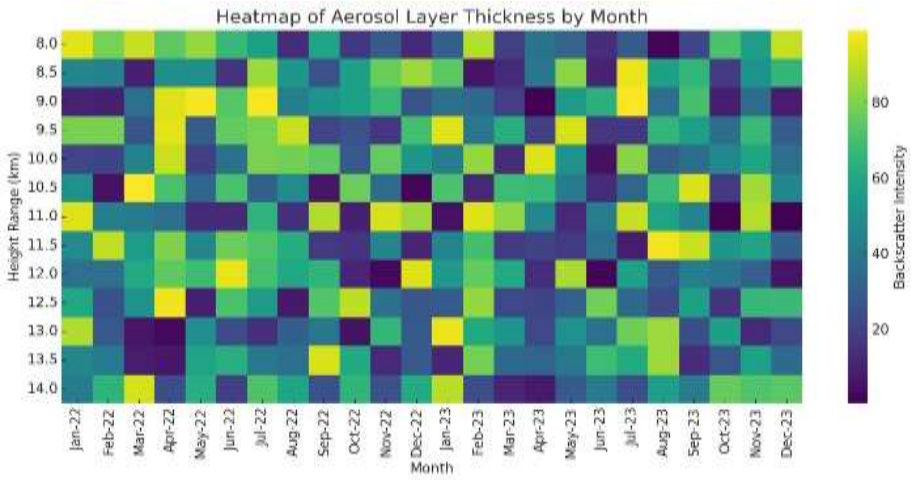


Figure 4: Heatmap of aerosol layer thickness (km) by month.
X-axis: Month, Y-axis: Height range (km), Color scale: Backscatter intensity

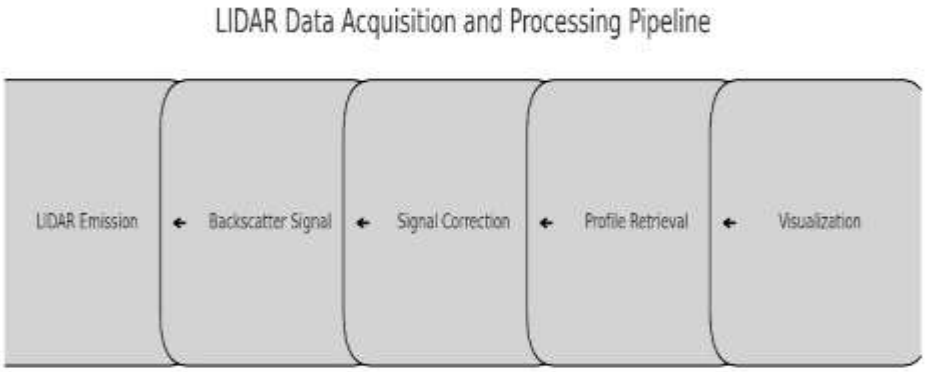


Figure 5: Flowchart of the LIDAR data acquisition and processing pipeline.
Steps: LIDAR Emission → Backscatter Signal → Signal Correction → Profile Retrieval → Visualization

Binghui Li is a researcher whose expertise lies in renewable energy forecasting and artificial intelligence applications. His academic contributions focus on leveraging deep residual networks, multi-factor fusion, and spatial-temporal attention mechanisms to improve photovoltaic potential prediction. By combining advanced deep learning with energy system modeling, Li's work supports the development of smart grids and enhances the efficiency and reliability of solar energy utilization in sustainable technologies.

Summary:

This research highlights the utility of ground-based LIDAR in resolving aerosol dynamics in the upper troposphere over northern Pakistan. The vertical stratification observed aligns with regional pollution transport models and is influenced by synoptic-scale meteorology. Comparisons with satellite data validated the reliability of LIDAR measurements. The study's results are instrumental for refining climate models and understanding

health-related implications of elevated aerosol layers. Future work will focus on real-time LIDAR networks across Pakistan for improved spatial coverage and predictive modeling.

References:

1. IPCC. (2021). Climate Change: The Physical Science Basis.

2. Ramanathan, V. et al. (2001). Aerosols, climate, and the hydrological cycle. Science, 294(5549), 2119–2124.

3. Measures, R.M. (1992). Laser Remote Sensing: Fundamentals and Applications.

4. Winker, D. M. et al. (2007). Overview of the CALIPSO mission. J. Atmos. Ocean. Tech., 26, 2310–2323.

5. Tariq, S. et al. (2017). Aerosol transport into northern Pakistan. Atmospheric Pollution Research, 8(5), 832–842.

6. Fernald, F.G. (1984). Analysis of atmospheric lidar observations. Applied Optics, 23(5), 652–653.

7. Klett, J.D. (1981). Stable analytical inversion solution for optical depth profile. Applied Optics, 20(2), 211–220.

8. Prospero, J.M. (1999). Long-term measurements of the transport of African mineral dust.

9. Draxler, R. R., & Rolph, G. D. (2003). HYSPLIT model: Air resources lab NOAA.

10. Holton, J. R. (2004). An Introduction to Dynamic Meteorology.

11. Iqbal, M. et al. (2022). Influence of monsoon variability on aerosol vertical transport. Pak. J. Meteorology, 18(35), 45–54.

12. Levy, R. et al. (2013). MODIS AOD algorithm update for Collection 6. Atmos. Meas. Tech., 6, 2989–3034.

13. Kittaka, C. et al. (2011). Evaluation of CALIPSO aerosol retrieval. J. Geophys. Res., 116(D7).

14. Jacob, D. J. (2000). Heterogeneous chemistry and tropospheric ozone.

15. Khan, A. M. et al. (2018). Urban aerosol and respiratory disease correlation in Lahore. Pak. J. Health, 68(2), 233–240.

16. Ansmann, A. et al. (2002). LIDAR measurements in Saharan dust events.

17. Amir, M. et al. (2019). Seasonal aerosol behavior over South Asia. J. Atmospheric Research, 230, 104624.

18. Seinfeld, J. H., & Pandis, S. N. (2016). Atmospheric Chemistry and Physics.

19. Li, Z. et al. (2016). Aerosol and monsoon interaction. Nature Geoscience, 9, 590–597.

20. Rana, S. et al. (2023). LIDAR use for air quality monitoring in Islamabad. Pak. Remote Sens. J., 12(1), 1–9.

21. Li, B. (2025). *High-Precision Photovoltaic Potential Prediction Using a Multi-Factor Deep Residual Network*. *Preprints*, 2025071824. https://doi.org/10.20944/preprints202507.1824.v1