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RESEARCH ARTICLE

Influence of seasonal variability and meteorological factors on airborne bioaerosols in a high-altitude environment of Ooty, Western Ghats: Insights into bacterial dynamics

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Abstract

Bioaerosols, comprising viable and non-viable biological particles, significantly influence atmospheric processes, climate modulation and human health. This study investigates the impact of climatic and atmospheric conditions on bioaerosol composition and microbial dynamics at high altitudes of Western Ghats, specifically at the ISRO ARFI Environmental Observatory in Ooty, Tamil Nadu, situated at 2520 meters above sea level. Bioaerosol samples were collected using a high-volume respirable dust sampler with a flow rate of 1.4 m^3/min over an 8-hour sampling period. Microbial enumeration was conducted through culture-based methods, including spread plate, streak plate and slant culture techniques on nutrient agar, Rose Bengal agar and Ken Knights agar media.

Results revealed seasonal variations in bacterial colony-forming units (CFU), with peak concentrations recorded during the post-monsoon and winter months (October–January). CFU counts ranged from 50 to 169 CFU/m^3, with the highest values observed in the central portion of the filter (169 ± 24.64 CFU/m^3) and lower values in the peripheral region (134 ± 14.03 CFU/m^3). Morphological characterisation and Gram staining of bacterial colonies indicated a diverse microbial population, with a predominance of Gram-positive rod-shaped bacteria. The study further highlighted that bacterial density was highest during February-May (134 ± 14.03 CFU/m^3) and lowest between June-September (50 ± 10.72 CFU/m^3), suggesting strong correlations with temperature, humidity and UV radiation.

The findings underscore the sensitivity of bioaerosol populations to altitude-related environmental stressors, aligning with previous studies that report reduced microbial diversity at higher elevations. This study enhances the understanding of airborne microbial ecology and provides a basis for future research employing molecular techniques, such as 16S rRNA sequencing, to elucidate microbial community dynamics. These insights are crucial for assessing bioaerosol contributions to atmospheric chemistry, air quality and potential public health implications.

Keywords

bioaerosols; climatic and atmospheric conditions; high-altitude environments; microbial diversity; microbial dynamics

Introduction

Bioaerosols are airborne particulate matter that contain microscopic biological entities, including viable (alive or dead) microbes, as well as plant and animal debris. These particles can be dispersed through their attachment to other particulate matter and are ubiquitous in both indoor and outdoor environments. The physical properties, composition and biological attributes of bioaerosols exhibit considerable variability and play a pivotal role in the dissemination of infectious agents, allergens and other sensitising substances (1). Exposure to bioaerosols can lead to a range of adverse human health outcomes, including infectious diseases, allergic responses, respiratory ailments and acute toxic effects. Bioaerosols are typically categorised into two broad classes: viable bioaerosols, encompassing living microorganisms such as bacteria, fungi and algae and non-viable bioaerosols, which include aerosolised pollen, insect excreta and plant matter (2-4).

The size spectrum of bioaerosols ranges from virus particles as small as 10 nanometres to large pollen grains measuring up to 100 micrometres in diameter. Pollen, being among the largest bioaerosols, is subject to gravitational settling, limiting its airborne residence time (5). Bioaerosol concentrations are generally highest within the planetary boundary layer (PBL) and decrease with increasing altitude. A multitude of biotic and abiotic factors, including climatic conditions, ultraviolet (UV) radiation, temperature and humidity, as well as the presence of dust or cloud particles, significantly influence the survival, distribution and activity of bioaerosols (6-8). These particles also exert profound effects on atmospheric dynamics, influencing microbial decomposition, the chemical composition of organic molecules and atmospheric chemistry. Furthermore, bioaerosols can impact climate through their roles in sunlight absorption and reflection and nucleation of cloud droplets and ice crystals, thus indirectly contributing to global climate modulation, while also posing a threat to human health (9-13).

This study explores the hypothesis that the decline in microorganism concentration and viability with altitude is influenced by factors such as reduced water availability, elevated UV radiation, lower temperatures and lower atmospheric pressure as observed at the ISRO ARFI Environmental Laboratory, located in the high-altitude region of Ooty, Tamil Nadu, India. The investigation employed culture-based techniques, including the spread plate method for enumeration and the streak plate and slant culture methods for microorganism isolation.

Materials and Methods

The study was conducted during the period of 2023–24 at the ISRO ARFI Environmental Observatory, situated at the Western Ghats of the Southern part of India, Tamil Nadu, India. The following subsections outline the methodologies employed for the collection, processing and analysis of samples, along with the materials utilised throughout the research.

Study site description

The research was conducted in the vicinity of Ooty, located within the Western Ghats of the Southern part of India. Renowned for its tranquil environment and distinct climatic conditions, Ooty's elevated position is one of the highest mountain ranges enhancing its unique environmental characteristics. The ISRO ARFI Environmental Observatory, situated at an altitude of 2520 m above sea level (Latitude - 11°25’27” N, Longitude - 76°43’27” E), plays a pivotal role in the region's scientific research.

Despite its natural beauty, Ooty faces a significant challenge due to its popularity as a hill station and tourist destination, resulting in substantial vehicular traffic, particularly during peak tourist seasons. The combustion of fossil fuels from these vehicles, alongside emissions from diesel generators and industrial activities, leads to the release of black carbon particles into the atmosphere (14). This phenomenon highlights the critical need for monitoring black carbon pollution and identifying the presence of bioaerosols to maintain the ecological balance and preserve the region's charm. The entirety of the research study was carried out at the ISRO ARFI Environmental Observatory, Ooty, Tamil Nadu.

Bioaerosol sample collection

A high-volume respirable dust sampler was utilised to collect the biogenic aerosols emitted by various plant and tree species. Quartz filter papers were employed to capture aerosols with particle sizes of 10 microns or smaller. These filter papers were replaced periodically (every 24 hr) during the sample collection process to ensure accurate results.

The sampler operates on the principle of particle separation via centrifugal forces. Ambient air containing suspended particles enters the system through a corrosion-resistant aluminium modular inlet pipe. As the air passes through the cyclone, the particulate matter is divided into two fractions: respirable dust and coarse, non-respirable dust. The centrifugal forces acting on the solid particles cause them to separate. The respirable fraction, which consists of smaller particles, continues through the cyclone and is directed toward the filter paper, which is positioned between the top cover and the filter adaptor assembly. The filter captures the respirable dust, while the blower exhausts the system's carrier air. The coarse particles are collected in the bottom of the sampling bottle (15-17).

Sample preparation

A 5×5 cm piece of filter paper containing the bioaerosol sample was taken and rinsed to remove the aerosol particles adsorbed on the filter surface using 10 mL of distilled water. The rinsed water was collected in a clean beaker for further processing.

Standardised weekly sampling approach for seasonal variability analysis

The study was conducted over three distinct seasonal periods in 2023-24: June-September, October-January and February-May, each spanning approximately four months. A systematic weekly sampling approach was employed to capture seasonal variability effectively. A total of 12-16 sampling events per period (one sampling per week) was conducted,

ensuring consistent data collection throughout the study. To minimise potential biases caused by short-term weather anomalies, sampling was evenly distributed across each period. Based on this approach, the total number of sampling events over the entire study duration was approximately 48 samplings.

Sample inoculation using the spread plate method

Agar media were prepared according to the type of microorganisms to be enumerated. In this study, nutrient agar was used for bacterial enumeration (18, 19), Rose Bengal agar for fungi (20, 21) and Ken Knights agar for actinomycetes (22, 23). The agar media were autoclaved and to minimise condensation, they were cooled to between 45 °C and 50 °C before pouring into Petri plates. Approximately 15-20 mL of media was poured into each plate, resulting in an agar layer of approximately 0.3 cm thickness. Once the media solidified, 1 mL of the bioaerosol sample was pipetted onto the surface of the agar.

A reusable glass or metal spreader was flame-sterilised by immersing it in alcohol. After sterilisation, the spreader was used to evenly distribute the inoculum across the solidified media. The spreader was rotated alternately to ensure uniform coverage. The plates were allowed to absorb the inoculum for 10 to 20 min before being incubated as necessary. The incubation times were 1 day for bacteria, 4 days for fungi and 7 days for actinomycetes. After the incubation period, the number of microbial colonies that developed was manually counted (24-29).

Calculation

Enumeration of colonies formed was done by manual counting method. The number of colony forming units (CFUs) in 10 mL of liquid sample was calculated using the formula:

CFU =

No. of colonies formed per plate × Dilution factor

Normally the count of microbes in air is expressed in CFU/m^3. So the average of each CFU is converted into CFU/m^3 of air by using the formula (30):

$$CFU/m^3 = \frac{\text{Average No.of.Colonies x 1000}}{\text{Sampling flow rate } \left(\frac{m^3}{min}\right) \text{ x sampling time (min)}}$$

Here the sampling flow rate of the instrument is 1.4 m^3/min and the sampling time is about 8 hr.

Results

Seasonal variations in airborne bacterial concentration

Airborne bacterial colony-forming units (CFU) exhibited distinct seasonal variations across the study period at the ISRO ARFI Environmental Observatory, Ooty, located in a high-altitude region (2520 m above sea level). The CFU values per cubic meter of air were highest during the summer season (February–May), reaching 134 ± 14.03 CFU/m^3 (corner portion) and 169 ± 24.64 CFU/m^3 (center portion) (Table 6, Fig. 2). Conversely, the lowest CFU values were recorded during the monsoon season (June–September), at 70 ± 14.61 CFU/m^3 (corner) and 50 ± 10.72 CFU/m^3 (center). This pattern suggests that bacterial abundance is significantly influenced by seasonal meteorological conditions, particularly temperature, humidity and precipitation (Fig. 1).

Temperature is a major determinant of microbial survival and proliferation. The highest bacterial CFU values during February–May correlated with the peak temperatures observed during this period (25.72 °C in 2023 and 25.07 °C in 2024) (Table 1, Fig. 1). This increase in bacterial load can be attributed to favourable conditions for microbial growth, enhanced airborne dispersal due to thermal updrafts and a reduction in precipitation-mediated deposition. Conversely, the lowest temperatures recorded during October–January (23.21 °C in 2023 and 23.14 °C in 2024) corresponded to an intermediate bacterial abundance of 100 ± 10.72 CFU/m^3 (corner portion) and 90 ± 20014.03 CFU/m^3 (centre portion). These findings indicate that while temperature plays a crucial role, other factors, such as humidity and rainfall, significantly influence bacterial dynamics.

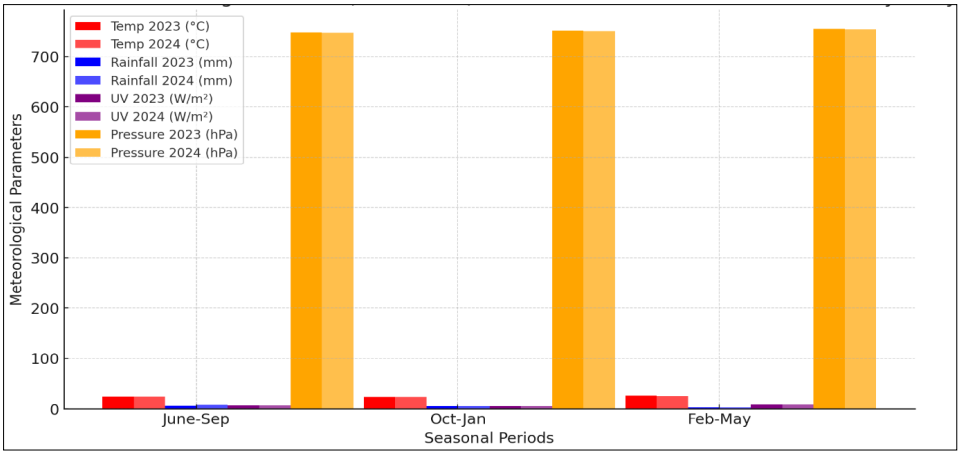


Fig. 1. Seasonal meteorological trends (2023-24) at ISRO ARFI Environmental Observatory, Ooty.

Table 1. Seasonal temperature (°C) (2023-2024) at the ISRO ARFI Environmental Observatory, Ooty

Period	2023 Average (°C)	2024 Average (°C)	2023 Std Dev (°C)	2024 Std Dev (°C)	2023 Min (°C)	2024 Min (°C)	2023 Max (°C)	2024 Max (°C)
June - September	24.12	23.80	0.47	0.55	23.63	23.29	24.67	24.33
October - January	23.21	23.14	0.69	0.62	22.73	22.62	24.23	24.04
February - May	25.72	25.07	1.13	1.33	24.14	23.36	26.80	26.42

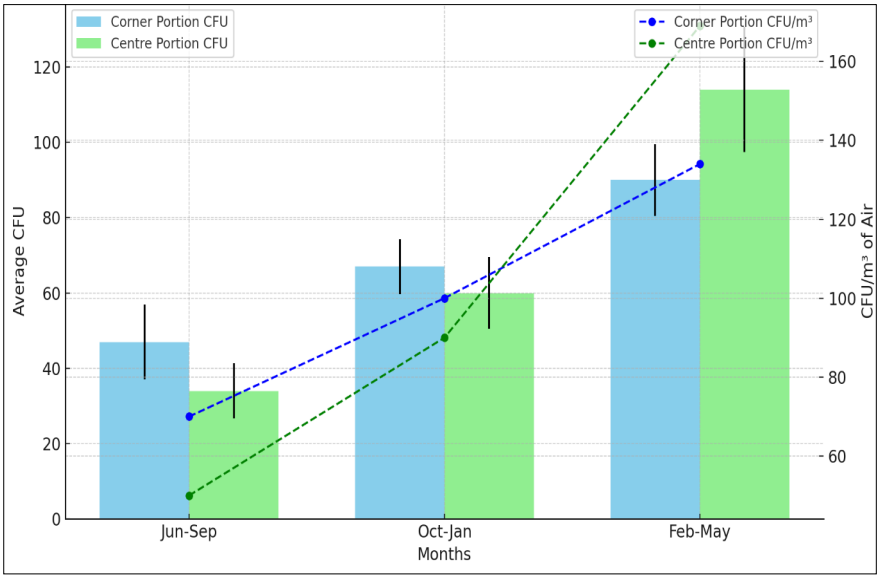


Fig. 2. Average bacterial colony-forming units (CFU) in aerosol particles and CFU/m^3 of air over the different months of 2023-2024.

Role of rainfall and humidity in bacterial abundance

The seasonal variation in rainfall and relative humidity was closely linked to bacterial concentration. Rainfall was highest in June–September (8.11 mm in 2024), coinciding with the lowest bacterial CFU counts (Table 2, Fig. 1). This suggests that rainfall contributes to the wet deposition of airborne bacteria, effectively reducing their atmospheric presence. Rain droplets act as scavenging agents, removing microbial particles from the air through impaction, diffusion and coagulation processes. This mechanism is well-supported by previous studies demonstrating the inverse relationship between precipitation and bioaerosol concentration in various environments.

Conversely, the lowest rainfall levels were observed in February-May (2.87 mm in 2024), which corresponded to the highest bacterial CFU values (Table 2, Fig. 3). The dry atmospheric conditions likely enhanced bacterial resuspension and airborne survival by minimising wet deposition processes. Additionally, a reduction in rainfall during this period coincided with lower humidity levels, which may have influenced bacterial community composition.

Humidity is another critical factor affecting bacterial viability and atmospheric persistence. The highest relative humidity was recorded in June-September (Table 3, Fig. 1), a period characterised by lower bacterial concentrations. This supports the hypothesis that higher humidity may enhance bacterial deposition onto surfaces, reducing their atmospheric presence. Additionally, increased humidity can alter bacterial physiology, affecting membrane integrity and metabolic activity.

On the other hand, lower humidity levels during February-May correlated with an increase in Gram-positive bacterial dominance (Table 9, Fig. 4). Gram-positive bacteria, such as cocci and spore-forming bacilli, are known to exhibit higher resistance to desiccation, allowing them to persist under dry conditions. In contrast, Gram-negative bacteria, which tend to be more sensitive to desiccation, were relatively more abundant in the high-humidity monsoon period. This highlights the selective pressure exerted by humidity on bacterial communities, favouring specific taxa based on their environmental resilience.

Influence of UV radiation on airborne bacterial composition

UV radiation exhibited strong seasonal variation, with peak values recorded during February-May (8.92 W/m^2 in 2023 and 8.73 W/m^2 in 2024) and the lowest values during October-January (5.46 W/m^2 in both years) (Table 4, Fig. 1). UV exposure is a well-documented stressor for airborne bacteria, inducing DNA damage and oxidative stress. Despite this, bacterial CFU values were highest during periods of elevated UV radiation (Fig. 3).

Table 2. Seasonal rainfall (mm) (2023–24) recorded at the ISRO ARFI Environmental Observatory, Ooty

Period	2023 Average (mm)	2024 Average (mm)	2023 Std Dev (mm)	2024 Std Dev (mm)	2023 Min (mm)	2024 Min (mm)	2023 Max (mm)	2024 Max (mm)
June - September	5.92	8.11	1.76	4.17	4.34	2.90	8.19	11.98
October - January	5.47	4.93	2.45	2.81	2.08	1.57	7.65	8.38
February - May	3.05	2.87	2.39	2.80	0.68	0.01	6.30	6.60

Table 3. Seasonal average relative humidity (%) (2023–24) recorded at the ISRO ARFI Environmental Observatory, Ooty

Period	2023 Average (mm)	2024 Average (mm)	2023 Std Dev (mm)	2024 Std Dev (mm)	2023 Min (mm)	2024 Min (mm)	2023 Max (mm)	2024 Max (mm)
June - September	5.92	8.11	1.76	4.17	4.34	2.90	8.19	11.98
October - January	5.47	4.93	2.45	2.81	2.08	1.57	7.65	8.38
February - May	3.05	2.87	2.39	2.80	0.68	0.01	6.30	6.60

Table 4. Seasonal average UV radiation (W/m^2) (2023–24) recorded at the ISRO ARFI Environmental Observatory, Ooty

Period	2023 Average (W/m^2)	2024 Average (W/m^2)	2023 Std Dev (W/m^2)	2024 Std Dev (W/m^2)	2023 Min (W/m^2)	2024 Min (W/m^2)	2023 Max (W/m^2)	2024 Max (W/m^2)
June - September	7.08	7.14	0.84	0.83	6.22	6.35	8.13	8.26
October - January	5.46	5.46	0.37	0.43	5.08	5.21	5.97	6.10
February - May	8.92	8.73	1.41	1.42	7.11	6.86	10.41	10.16

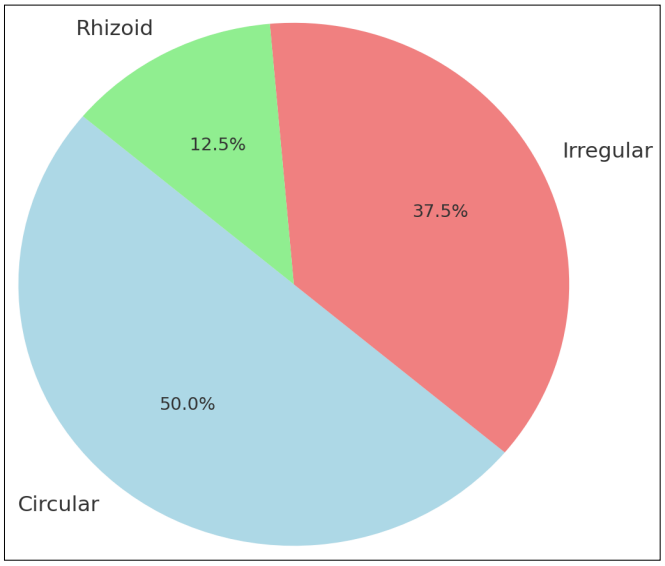


Fig. 3. Distribution pattern of bacterial morphotypes in airborne bioaerosols.

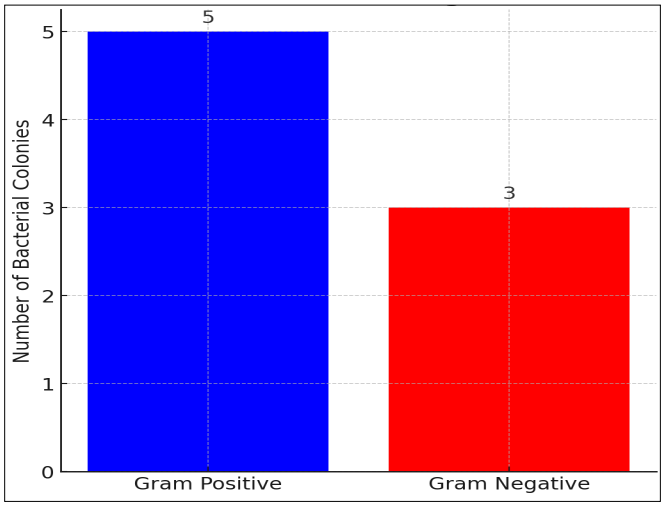


Fig. 4. Distribution pattern of Gram-positive and Gram-negative bacteria in airborne bioaerosols.

One possible explanation for this trend is the presence of UV-resistant bacterial species. The dominance of Gram-positive coccoid bacteria (Colony 7 and 8, Table 9, Fig. 4) during February–May suggests that these organisms possess adaptive mechanisms, such as thick peptidoglycan layers and efficient DNA repair systems, enabling them to withstand UV-induced damage. Additionally, bacteria forming pigmented colonies (such as Colony 2, which exhibited a yellow slimy morphology, Table 8, Fig. 3) may produce carotenoids that provide photo-protection.

Seasonal variability in bacterial morphology and growth characteristics

The bacterial colonies exhibited distinct morphological features across seasons, reflecting adaptation to varying environmental stressors (Table 7 and 8, Fig. 3).

During February-May, larger bacterial colonies were predominant, including Colony 2 (3 mm, yellow, slimy) and Colony 6 (2 mm, yellowish-white, smooth). These bacteria likely thrived under conditions of higher temperature and UV radiation, exhibiting enhanced growth rates and biofilm formation as protective mechanisms.

In contrast, during June-September, smaller bacterial colonies were more abundant, including Colony 1 (0.5 mm, punctiform, creamy white) and Colony 4 (0.4 mm, transparent). The prevalence of smaller colonies suggests adaptation to high humidity and rainfall conditions, where bioaerosol survival depends more on surface attachment and reduced metabolic activity. Furthermore, the monsoon season favoured biofilm-forming Gram-negative bacteria (Colony 2, 4 and 6, Table 9, Fig. 4), which are better suited for survival in moist conditions.

Table 5. Seasonal average atmospheric pressure (hPa) (2023-24) recorded at the ISRO ARFI Environmental Observatory, Ooty

Period	2023 Average (hPa)	2024 Average (hPa)	2023 Std Dev (hPa)	2024 Std Dev (hPa)	2023 Min (hPa)	2024 Min (hPa)	2023 Max (hPa)	2024 Max (hPa)
June - September	748.5	747.5	1.29	1.29	747	746	750	749
October - January	752.5	751.5	1.29	1.29	751	750	754	753
February - May	755.5	754.5	1.29	1.29	754	753	757	756

Table 6. Bacterial colony forming units in aerosol particles in the year 2023-2024

Month	Part of filter paper	Average CFU	SD	CFU/ m^3 of air	SD
June - Sep	Corner portion of filter	47±9.9	17	70±14.61	25.3
	Centre portion of filter	34±7.3	12.5	50±10.72	18.56
Oct- Jan	Corner portion of filter	67±7.3	12.5	100±10.72	18.56
	Centre portion of filter	60±9.5	16.3	90±14.03	24.31
Feb-May	Corner portion of filter	90±9.5	16.3	134±14.03	24.31
	Centre portion of filter	114±16.6	28.7	169±24.64	42.68

Table 7. Morphological features of the bacterial colonies cultured from the bioaerosol sample

Bacterial Colony	No. of colonies / Petri plate	Diameter of the colony	Size of the colony (πr^2, mm^2)	Form	Elevation	Colour	Characteristics
Colony 1	11	0.5 mm	0.2	Punctiform	Convex	Creamy white	Slimy colony
Colony 2	6	3 mm	7.06	Circular	Raised	Yellow	Slimy colony
Colony 3	2	1 mm	0.78	Irregular	Flat	Creamy white	Mucous-like colony
Colony 4	2	0.4 mm	0.13	Circular	Flat	Transparent	Smooth colony
Colony 5	1	1 cm (length)	0.28	Irregular, hairy colonies (rhizoid)	Flat, Thread-like	White	Smooth colony
Colony 6	5	2 mm	3.14	Irregular	Flat	Yellowish white	Smooth colony
Colony 7	5	0.9 mm	0.63	Irregular	Raised at the centre of the colony	Reddish centre with yellowish border	Slimy colony

Impact of atmospheric pressure on bacterial aerosolisation

Atmospheric pressure also exhibited seasonal variation, with lower pressure recorded in June-September (747.5 hPa in 2024) and higher pressure in February-May (754.5 hPa in 2024) (Table 5, Fig. 1). Lower pressure conditions have been linked to increased bacterial deposition, whereas higher pressure may enhance bacterial resuspension and atmospheric persistence. The relationship between pressure and bioaerosol dynamics warrants further investigation, as it may influence bacterial dispersal patterns, particularly in high-altitude environments.

Interactions between meteorological parameters and bacterial dynamics

The complex interplay between temperature, humidity, rainfall, UV radiation and atmospheric pressure significantly influenced airborne bacterial dynamics. The following key relationships were observed (Fig. 1, Fig. 2):

1. Higher temperatures, lower humidity and increased UV radiation (February-May) promoted bacterial dispersal, favouring UV-resistant Gram-positive bacteria (Fig. 4).
2. High humidity and rainfall (June-September) led to reduced bacterial abundance and favoured Gram-negative bacteria with biofilm-forming capabilities (Fig. 3).
3. Intermediate conditions (October-January) supported a mixed bacterial population, with gradual shifts in colony morphology and composition.

Discussion

Seasonal variations in airborne bacterial concentration

The observed seasonal variations in airborne bacterial colony -forming units (CFU/m^3) highlight the strong influence of meteorological factors on microbial aerosolisation and survival. CFU values were highest during the summer season (February-May), reaching 134 ± 14.03 CFU/m^3 in the corner portion and 169 ± 24.64 CFU/m^3 in the centre portion (Table 6, Fig. 2). In contrast, the lowest CFU values were recorded during the monsoon season (June-September), with 70 ± 14.61 CFU/m^3 (corner) and 50 ± 10.72 CFU/m^3 (centre), demonstrating the suppressive effects of high precipitation and humidity on bacterial abundance.

Temperature played a crucial role in microbial proliferation, with peak CFU values aligning with the highest recorded temperatures of 25.72°C in 2023 and 25.07°C in 2024 (Table 1, Fig. 1). Elevated temperatures likely facilitated bacterial survival and dispersal through enhanced thermal updrafts and reduced wet deposition (27, 28). Conversely, the intermediate bacterial counts observed during October-January (100 ± 10.72 CFU/m^3 in the corner and 90 ± 14.03 CFU/m^3 in the center) suggest that, while the temperature is a key driver, other environmental factors such as rainfall and humidity also significantly modulate bacterial presence in aerosols.

Role of rainfall and humidity in bacterial abundance

Rainfall exhibited an inverse correlation with airborne bacterial CFU counts, with peak precipitation recorded in June-September (8.11 mm in 2024) coinciding with the lowest bacterial concentrations (Table 2, Fig. 1). This supports the hypothesis that wet deposition mechanisms, including impaction, diffusion and coagulation, play a significant role in removing airborne microbes. Previous studies have similarly demonstrated that increased precipitation leads to a marked decline in bioaerosol concentrations (27, 28, 31).

Lower rainfall levels during February-May (2.87 mm in 2024) corresponded with the highest CFU counts (Table 2, Fig. 2), likely due to reduced wet deposition and enhanced resuspension of bacterial particles. Additionally, relative humidity was highest in June-September (Table 3, Fig. 1), further contributing to bacterial removal from the atmosphere through surface attachment. Lower humidity levels during February-May favoured the dominance of Gram-positive bacteria, such as cocci and spore-forming bacilli (Table 9, Fig. 4), which are known for their resistance to desiccation. In contrast, the high-humidity monsoon period supported a relatively greater abundance of Gram-negative bacteria, which thrive in moist environments.

Influence of UV radiation on airborne bacterial composition

UV radiation peaked during February-May (8.92 W/m^2 in 2023 and 8.73 W/m^2 in 2024) and was lowest during October-January (5.46 W/m^2) (Table 4, Fig. 1). Despite the well-documented detrimental effects of UV radiation on bacterial viability, CFU counts were highest during periods of elevated UV exposure. This suggests that bacterial communities in the study region may possess adaptive mechanisms to counteract UV-induced stress.

The dominance of Gram-positive coccoid bacteria (Colony 7 and 8, Table 9, Fig. 4) during February-May indicates that these organisms exhibit increased UV resistance, potentially due to thick peptidoglycan layers and robust DNA repair mechanisms. Additionally, pigmented bacterial colonies, such as Colony 2 (yellow, slimy morphology, Table 8, Fig. 3), likely produce carotenoid pigments that offer photo

Table 8. Morphological characteristics of the bacterial colonies

Bacterial colony	No. of colonies / petri plate	Size	Form	Elevation	Colour	characteristics
Colony 1	11	0.5 mm	Circular (punctiform)	Convex	Creamy white	Slimy colony
Colony 2	6	3 mm	Circular	Raised	yellow	Slimy colony
Colony 3	2	1 mm	Irregular	Flat	Creamy white	Mucous like colony
Colony 4	2	0.4 mm	Circular	Flat	Transparent	Smooth colony
Colony 5	1	1 cm in length	Irregular hairy colonies (rhizoid)	Flat, Thread-like	White	Smooth colony
Colony 6	5	2 mm	Irregular	Flat	Yellowish white	Smooth colony
Colony 7	1	1.5 mm	Circular, filamentous	Convex	Creamy white centre and transparent hyphae at border	Smooth colony
Colony 8	5	1 mm	Irregular	Raised at the centre of the colony	Reddish centre with yellowish border	Slimy colony

protection against UV damage. This aligns with earlier findings that reported a prevalence of UV-resistant bacterial species in high-radiation environments (32).

Seasonal variability in bacterial morphology and growth characteristics

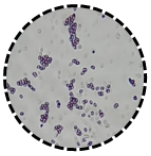
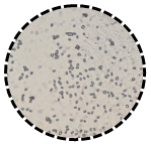
Bacterial colonies displayed distinct morphological variations across seasons, suggesting differential adaptations to environmental stressors (Tables 7 and 8, Fig. 3). During February-May, larger bacterial colonies were predominant, including Colony 2 (3 mm, yellow, slimy) and Colony 6 (2 mm, yellowish-white, smooth), likely indicative of enhanced metabolic activity and biofilm formation under high-temperature and low-humidity conditions which coincides with earlier research results (33, 34).

Conversely, June-September was characterised by the prevalence of smaller bacterial colonies, such as Colony 1 (0.5 mm, punctiform, creamy white) and Colony 4 (0.4 mm, transparent), suggesting adaptation to high humidity and rainfall. The dominance of biofilm-forming Gram-negative bacteria (Colony 2, 4 and 6, Table 9, Fig. 4) in this season aligns with their known preference for moist environments.

Impact of atmospheric pressure on bacterial aerosolisation

Atmospheric pressure exhibited seasonal fluctuations, with lower values recorded in June-September (747.5 hPa in 2024) and higher values in February-May (754.5 hPa in 2024) (Table 5, Fig. 1). Higher pressure conditions are often associated with enhanced bacterial resuspension and atmospheric persistence, whereas lower pressure may facilitate microbial

Table 9. Observations made under Gram staining

Bacterial colony No.	Gram-positive / negative	Shape	Image
Colony 1	Positive	Rod shaped	
Colony 2	Negative	Rod shaped	
Colony 3	Positive	Rod shaped	
Colony 4	Negative	Rod shaped	
Colony 5	Positive	Elongated Rod shaped	
Colony 6	Negative	Rod shaped	
Colony 7	Positive	Coccoid shaped	
Colony 8	Positive	Coccoid shaped	
	No. of. Gram-positive bacteria colonies		**5**
	No. of. Gram-negative bacteria colonies		**3**

deposition which was already reported (35, 36). Although this study provides preliminary evidence for pressure-mediated effects on bioaerosol dynamics, further research is needed to elucidate the underlying mechanisms, particularly in high-altitude environments.

Interactions Between Meteorological Parameters and Bacterial Dynamics

The complex interplay between meteorological factors significantly influenced airborne bacterial populations, which has similar trends to earlier research results (31-33, 35,36).

Key relationships include (Fig. 1, 2):

- Higher temperatures, lower humidity and increased UV radiation (February-May) promoted bacterial dispersal, favouring UV-resistant Gram-positive bacteria (Fig. 4).
- High humidity and rainfall (June-September) led to reduced bacterial abundance and favoured Gram-negative bacteria with biofilm-forming capabilities (Fig. 3, 4).
- Intermediate climatic conditions (October-January) supported a mixed bacterial population with gradual shifts in colony morphology and composition.

Implications for high-altitude aerosol microbiology

The study site's high-altitude location contributed to the overall lower bacterial densities (50-150 CFU/m^3) (Fig. 2). The absence of fungal colonies further supports the dominance of bacterial communities. This trend aligns with previous research (31-33), which documented reduced bacterial densities at higher elevations due to extreme climatic conditions, including low temperatures, reduced air pressure and high UV exposure.

The altitude-related decline in microbial viability is further corroborated by previous studies (34-35), which reported significant reductions in airborne bacterial abundance across elevated terrains. Other research demonstrated that at altitudes above 600 m, viable bacterial cell counts declined drastically (34-37). These findings collectively highlight the ecological constraints imposed by altitude on microbial aerosols.

Conclusion

This study provides a comprehensive assessment of the influence of seasonal variability and meteorological factors on airborne bioaerosols in a high-altitude environment of the Western Ghats, specifically at the ISRO ARFI Environmental Observatory in Ooty, Tamil Nadu, India, during 2023-2024. The findings reveal pronounced seasonal fluctuations in airborne bacterial concentrations, which are strongly regulated by meteorological parameters, including temperature, humidity, rainfall, ultraviolet (UV) radiation and atmospheric pressure. The highest bacterial colony-forming unit (CFU) concentrations were recorded during the summer season (February-May), reaching 134 ± 14.03 CFU/m^3 (corner portion) and 169 ± 24.64 CFU/m^3 (centre portion), while the lowest values were observed during the monsoon season (June-September), with 70 ± 14.61 CFU/m^3 (corner) and 50 ± 10.72 CFU/m^3 (centre). These variations highlight the critical role of temperature in bacterial survival and dispersal, where elevated temperatures favour microbial proliferation and aerosolisation. Conversely, increased rainfall during the monsoon season contributed to a significant decline in bacterial abundance, likely due to wet deposition mechanisms that remove bioaerosols from the atmosphere.

Humidity also played a pivotal role in shaping bacterial community composition. The higher humidity during the monsoon period favoured the predominance of Gram-negative, biofilm-forming bacteria, which exhibit resilience to moist conditions, whereas lower humidity during the summer season was associated with an increased dominance of Gram-positive bacteria with enhanced desiccation resistance. Additionally, variations in UV radiation were found to significantly impact bacterial survival. The peak UV exposure in summer coincided with the highest bacterial CFU values, suggesting the dominance of UV-resistant bacterial species, including pigmented and thick-peptidoglycan-layered Gram-positive bacteria that exhibit adaptive responses to elevated radiation stress. Morphological characterisation of bacterial colonies revealed distinct seasonal trends, with larger, metabolically active colonies dominating in summer, while smaller, punctiform colonies were more prevalent during the monsoon season. These shifts likely reflect bacterial adaptation to fluctuating environmental stressors. Furthermore, atmospheric pressure variations were observed to influence bacterial aerosolisation, with lower pressure during the monsoon season potentially facilitating bacterial deposition and higher pressure in summer enhancing bioaerosol resuspension. The findings of this study are consistent with previous research indicating that high-altitude environments exhibit lower bacterial densities due to extreme climatic conditions (27-29, 33-37). The observed trends further support the hypothesis that microbial community structure is shaped by altitude-related environmental stressors, including low temperatures, reduced atmospheric pressure and high UV radiation, all of which impose constraints on bacterial viability and diversity.

Overall, this study provides critical insights into the intricate interplay between altitude, meteorological conditions and airborne microbial dynamics. The results underscore the ecological sensitivity of airborne bioaerosols to environmental fluctuations, offering valuable implications for atmospheric microbiology, climate change studies and air quality assessment. Notably, the observed seasonal trends have significant implications for air quality, respiratory health and microbial ecology. Periods of high bacterial concentration, particularly during February-May, may coincide with an increased risk of respiratory infections and allergic reactions due to elevated exposure to airborne pathogens and allergens. Moreover, the persistence of Gram-negative bacteria during the monsoon season raises concerns regarding potential endotoxin exposure, which may have broader public health implications. Understanding these seasonal trends is crucial for predicting the impacts of climate change on airborne microbial populations and developing strategies to mitigate bioaerosol-related health risks. Future research should integrate molecular techniques such as 16S rRNA sequencing and metagenomics to further elucidate microbial community

composition, functional potential and broader ecological implications. Additionally, long-term monitoring of airborne microbial populations in high-altitude regions is necessary to assess how climate variability influences microbial dispersal and survival. Such investigations will contribute to a deeper understanding of microbial biogeography and its interactions with atmospheric processes, ultimately informing policies related to air quality management, infectious disease surveillance and environmental monitoring in high-altitude ecosystems.

Future perspectives

Building on the insights gained from this study, several key research directions should be pursued to enhance our understanding of bioaerosol dynamics in high-altitude environments:

Molecular characterisation and functional analysis: Future studies should employ advanced molecular techniques such as 16S rRNA sequencing and metagenomic analyses to identify microbial taxa with greater precision. These approaches will provide insights into microbial community structure, diversity and functional potential, allowing for a deeper understanding of the roles played by airborne microorganisms in atmospheric processes.

Longitudinal and multi-site monitoring: Extending the temporal and spatial scope of bioaerosol studies by conducting multi-year monitoring across multiple high-altitude locations will help capture long-term trends and regional variations. This will be crucial in assessing the impact of climate change on microbial aerosol composition and dispersal patterns.

Impact of air pollutants and anthropogenic activities: Investigating the influence of black carbon and other airborne pollutants on bioaerosol viability and composition will provide valuable insights into the interactions between microbial aerosols and anthropogenic emissions. Understanding these relationships will be essential for developing strategies to mitigate pollution-related health risks.

Atmospheric microbial survival mechanisms: Experimental studies simulating high-altitude atmospheric conditions in controlled laboratory settings can shed light on microbial adaptation and survival mechanisms under extreme stressors such as desiccation, UV radiation and oxidative stress.

Role of bioaerosols in climate regulation: Given the ability of bioaerosols to influence cloud formation and atmospheric chemistry, future research should focus on quantifying their role in cloud condensation nuclei (CCN) formation and their potential contributions to climate feedback mechanisms.

By integrating these approaches, future studies will not only refine our understanding of airborne microbial ecology but also provide critical insights into bioaerosol-mediated interactions between the biosphere and atmosphere, with implications for climate science, public health and environmental sustainability.

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Authors' contributions

All the authors contributed equally to the research and writing of this article

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