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Air Quality Assessment using *Phaeophyscia hispidula* as a Bioindicator in Mount Abu: Potential Toxic Element Accumulation and Physiological Effects

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ABSTRACT

The present study assessed air pollution in Mount Abu, by using passive biomonitoring utilizing a foliose lichen *Phaeophyscia hispidula* (Ach.) Moberg, collected from four different locations. We examined potentially toxic elements (PTEs) accumulation and physiological parameters such as chlorophyll *a*, *b*, total chlorophyll, and carotenoids. The concentrations of PTEs varied significantly from site to site, with the order being Fe > Zn > Pb > Ni > Cu > Cd. The maximum concentrations were those of Fe (156.57 to 169.83 mg/kg DW) and Zn (15.10 to 21.12 mg/kg DW), while minimum for Cd (0.018 to 0.074 mg/kg DW) and Cu (0.596 to 0.690 mg/kg DW). Nakki Lake Road was the the highest polluted site, while Sunset Point showed the lowest levels. Physiological parameters demonstrated inverse correlation with pollution, with total chlorophyll (0.169-0.343 mg g^{-1} FW) and carotenoids (0.103-0.173 mg g^{-1} FW) decreasing at polluted sites. In nut shell, *P. hispidula* has once again proved itself as an effective biomonitor for air quality analysis in mountain ecosystems.

Keywords: Lichen, Pollution, Hill station, Rajasthan

INTRODUCTION

Air pollution remains a severe problem despite technical advances that have improved air quality in some locations (Briffa *et al.,* 2020; Ukaogo *et al.,* 2020). Anthropogenic greenhouse gas emissions and atmospheric contamination exacerbate air pollution and climate change (Pacyna and Pacyna, 2001; Ali *et al.,* 2019).

According to Abas (2021) and Thakur *et al.* (2024), lichens serve as cost-effective and best biomonitors for air quality. Lack of protective structures allows them to absorb nutrients and pollutants from the atmosphere, making them reliable bioindicators (Osyczka and Rola, 2019; Rola *et al.,* 2019). Their physiological and cellular changes in response to environmental changes make them useful biological indicators (Bačkor and Loppi, 2009; Frati and Brunialti, 2023; Stanton *et al.,* 2023; Yang *et al.,* 2023).

Despite Mount Abu's unique ecosystem facing environmental challenges, the state of Rajasthan lacks significant research on lichen biomonitoring, with only taxonomic studies of lichens available (Awasthi and Singh, 1979; Bajpai *et al.,* 2015; 2024; Sinha *et al.,* 2015). However, research in India has shown successful lichen biomonitoring across various centers (Bajpai *et al.,* 2009; 2011; 2014; Shukla and Upreti, 2007a; 2007b; 2012; Maurya *et al.,* 2024).

In the present work, the most common foliose lichen in the area, the *Phaeophyscia hispidula* (Ach.) Moberg, is used for passive biomonitoring in order to evaluate the air quality in different localities of the hill station situated at Mount Abu. The correlation between chl *a*, chl *b*, total chl, and carotenoid along with distribution of PTEs (Cd, Cu, Fe, Pb, Ni, and Zn) were also studied. This paper is a groundbreaking attempt to validate lichens as useful bioindicators for assessing atmospheric pollution in undulating and hilly habitats by establishing baseline environmental monitoring data for the state.

MATERIAL AND METHODS

The study was performed at an elevation between 1,097-1,603 m in Mount Abu, Sirohi district, Rajasthan, India (24°31′–24°43′N, 72°38′–72°53′E). Four sampling sites were strategically selected across the study region based on predetermined criteria to ensure representative coverage of different pollution scenarios and environmental conditions, that includes (i) variation in dominant pollution sources ranging from heavy vehicular traffic and industrial emissions to residential activities and background conditions, (ii) different traffic density patterns from high-traffic urban intersections to low-traffic rural areas, (iii) diverse land use types including commercial, industrial, residential, and rural/background zones, and (iv) accessibility and safety considerations for consistent field sampling (**Table 1**). *Phaeophyscia hispidula* samples were obtained from healthy tree bark at 1.5-2.0 m height using equipments (chisel and hammer) in March 2023 following biomonitoring methods of Bajpai *et al*. (2009, 2014) and Shukla and Upreti (2007a, 2012). The samples were then stored in labeled paper bags, and transferred to the laboratory within 24 hours. Morphological and anatomical confirmation was attained via microscopic examination utilizing the Olympus stereozoom dissecting microscope (SZX10) and the Olympus compound microscope (BX53). The standard protocols for chemical testing encompassed UV fluorescence analysis, color spot test, and thin-layer chromatography, employing solvent system C as outlined in the methodologies (Awasthi, 2007; Orange *et al.,* 2001).

A soft brush was used to clean samples under a dissecting microscope in order to remove contaminants during laboratory processing. After air-drying at room temperature for 48–72 hours until consistent weight, cleaned samples were ground to fine powder using a separate mortar and pestle and analyzed for PTEs and physiological parameters (chl *a*, chl *b*, total chl, carotenoid).

Table 1: Characteristics of sampling locations selected for lichen collection at Mount Abu, Rajasthan, India.

Location	Coordinates	Elevation (m)	Pollution Source /Traffic patterns
Oriya Road	24.628689°N 72.746105°E	1154	High vehicular traffic
Gurusikhar	24.645493°N 72.772756°E	1603	Highest peak point, moderate traffic
Nakki Lake Road	24.593860°N 72.706576°E	1097	Heavily traffic, maximum anthropogenic activites
Sunset Point	24.5876°N 72.7172516°E	1116	Popular tourist spot, forest area

Physiological and Biochemical Analyses

After exposure to urban pollution, parallel groups of lichen thalli were tested for physiological characteristics. Lichen samples were used for the estimation of photosynthetic pigments (chl *a*, chl *b*, total chl, and carotenoids) and all experiments were done in triplicate.

Chlorophyll and Carotenoid Content

About 0.5 g samples were ground with 0.25 g calcium carbonate and 5 ml cooled 80% acetone (Merck, analytical grade) in the dark, photosynthetic pigments (chl *a*, chl *b*, total chl, and carotenoids) were extracted and centrifuged for 10 minutes at 10,000 rpm. A UV scanning spectrophotometer (Thermo Fisher Scientific) was used to evaluate the supernatant at 663 and 645 nm for the chlorophyll content (Arnon, 1949) and at 480 and 510 nm for the total carotenoids (Parsons *et al.,* 1984). All pigment values were calculated in mg g^{-1} fresh weight (FW).

Potentially Toxic Elements Analysis

The lichen thalli were dried at 60°C in oven for 24 hours before being crushed into a fine powder. Samples weighing 1.0 g were dissolved in a 9:1 volume ratio of concentrated HNO_3 and $HClO_4$ for two hours. The dissolved materials were filtered using Whatman filter paper no. 42 and diluted with double-distilled water to 10 ml. An Agilent 7500ce ICP-MS measured element counts after 10 times dilution. Certified PTEs and metalloid reference materials from E-Merck, Germany, were used for analytical calibration. These standards ensured calibration precision and quality control in each analytical run. Method validation in triplicate analysis of quality control specimens demonstrated acceptable precision, with all readings within ±1.50% of certified reference values. Recovery studies fortified samples with precise proportions of target elements and obtained recovery percentages above 98% for Zn, Cu, Cd, Fe, Pb, and Ni, validating the analytical method. For every element under analysis, the detection limit was set at 1 µg l^{-1} (Bajpai *et al.,* 2023).

Statistical Analysis

Graphs were prepared as mean values with standard deviations based on three technical replicates using GraphPad Prism version 8.0.2 (263). Prior to statistical analysis, outlier identification and normality assessment were conducted using the Shapiro-Wilk test, with no outliers detected and normality confirmed for all parameters. Variance homogeneity was evaluated using Levene's test, confirming equal standard deviations across treatment groups. One-way analysis of variance (ANOVA) was performed to assess the effects of different sampling locations on physiological parameters and potentially toxic elements concentrations in lichen thalli, followed by Tukey's Honestly Significant Difference (HSD) test for post-hoc multiple comparisons among treatment means. All statistical analyses were performed with the significance level set at $p < 0.05$.

RESULTS

Analysis of Photosynthetic pigments across various locations in Mount Abu

In all samples analyzed (**Figure 1, Table 2**), there was a notable reduction in chlorophyll content across various forms. Chl *a* levels ranged from 0.108 to 0.244 mg g^{-1} fresh weight (FW) (**Figure 1A**), with the highest concentration observed at Sunset Point (0.244 ± 0.015 mg g^{-1}), and the lowest levels recorded at Nakki Lake Road (0.108 ± 0.007 mg g^{-1}).

Chl *b* showed a similar pattern, decreasing from 0.062 to 0.117 mg g^{-1} fresh weight (FW) (**Figure 1B**), with the highest levels recorded at Sunset Point (0.117 ± 0.018 mg g^{-1}), suggesting optimal lichen health conditions. In contrast, the lowest chl *b* concentrations were observed at Nakki Lake Road (0.062 ± 0.006 mg g^{-1}), followed by Oriya Road (0.069 ± 0.009 mg g^{-1}) and Gurusikhar (0.071 ± 0.008 mg g^{-1}), indicating significant stress on lichen in these areas (**Figure 1B**).

The total chl content, combining both forms, ranged between 0.169 to 0.343 mg g^{-1} fresh weight (**Figure 1C**) and was highest at Sunset Point (0.343 ± 0.052 mg g^{-1}), while the lowest levels were found at Nakki Lake Road (0.169 ± 0.014 mg g^{-1}), followed by Oriya Road (0.220 ± 0.029 mg g^{-1}) and Gurusikhar (0.237 ± 0.018 mg g^{-1}) (**Figure 1C**). These low levels of total chl highlight a general decline in the photosynthetic potential of lichen exposed to pollutants, further supporting the hypothesis that urban air quality is negatively affecting lichen health.

Conversely, carotenoid levels, which help protect against oxidative damage, showed variation, ranged from 0.103 to 0.173 mg g^{-1} fresh weight (FW) (**Figure 1D**) and were lowest at Nakki Lake Road (0.103 ± 0.004 mg g^{-1}) while highest at Sunset Point (0.173 ± 0.009 mg g^{-1}), followed by Gurusikhar (0.154 ± 0.025 mg g^{-1}) and Oriya Road (0.141 ± 0.022 mg g^{-1}) (**Figure 1D**), indicating a defensive response by the lichen to mitigate the damage caused by pollutants.

Overall, the highest chl content was consistently found at Sunset Point, while Nakki Lake Road, which is subject to higher pollution, exhibited the most substantial reductions in chl content, suggesting a strong negative impact of air quality on lichen health.

Table 2: Chlorophyll and carotenoid content in lichen samples collected from four different locations in Mount Abu. Data represents mean ± standard deviation values for photosynthetic pigments (chl *a*, chl *b*, total chl, and carotenoids) (n=3, expressed in mg g^{-1} fresh weight).

Parameter	Gurusikhar	Nakki Lake Road	Oriya Road	Sunset Point
Chl *a*	0.165 ± 0.015	0.108 ± 0.007	0.157 ± 0.017	0.244 ± 0.015
Chl *b*	0.071 ± 0.008	0.062 ± 0.006	0.069 ± 0.009	0.117 ± 0.018
Total Chl	0.237 ± 0.018	0.169 ± 0.014	0.220 ± 0.029	0.343 ± 0.052
Carotenoid	0.154 ± 0.025	0.103 ± 0.004	0.141 ± 0.022	0.173 ± 0.009

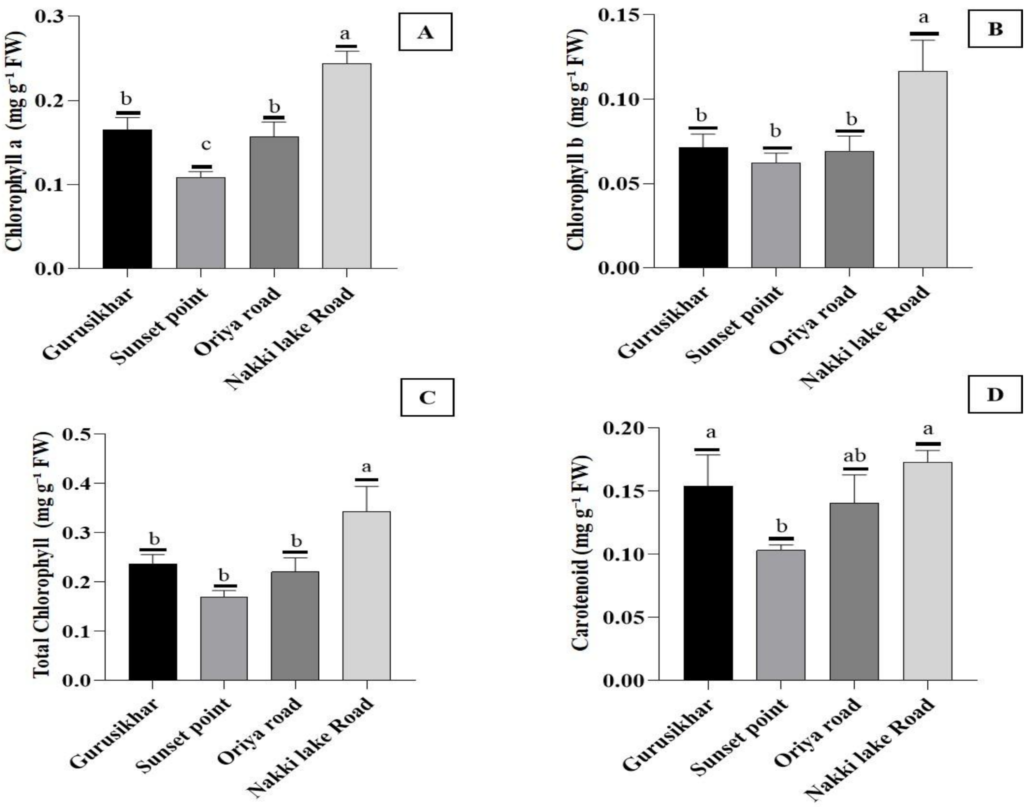

Figure 1: Chlorophyll and carotenoid content (mg g^{-1} FW) at four locations in Mount Abu. Bar graphs showing (A) chl *a*, (B) chl *b*, (C) total chl, and (D) carotenoid measured in mg g^{-1} fresh weight (FW) at four different locations. Values represent means ± standard deviation. Different letters above bars indicate statistically significant differences between locations ($p < 0.05$).

PTEs Analysis

The concentrations of six PTEs were evaluated in the current research Zn, Pb, Ni, Cu, Cd, and Fe. The findings reveal a significant variation in metal concentrations, highlighting the potential of *P. hispidula* as bioindicator for monitoring environmental pollution. The PTEs ranked by abundance as follows: Fe > Zn > Pb > Ni > Cu > Cd (**Table 3, Figure 2**).

Copper (Cu) concentrations ranged from 0.596 mg/kg to 0.690 mg/kg, with the highest levels found at Oriya Road (0.690 ± 0.028 mg/kg) and Nakki Lake Road (0.638 ± 0.048 mg/kg). The lowest levels were recorded at Gurusikhar (0.596 ± 0.062 mg/kg), while Sunset Point showed intermediate levels (0.638 ± 0.121 mg/kg) (**Figure 2A**). Increased Cu levels might reflect pollution from metal processing or traffic emissions.

Cadmium (Cd) levels varied between 0.018 mg/kg and 0.074 mg/kg, with higher concentrations observed at Nakki Lake Road (0.074 ± 0.007 mg/kg) and Gurusikhar (0.071 ± 0.008 mg/kg). The lowest levels were recorded at Sunset Point (0.018 ± 0.008 mg/kg) and Oriya Road (0.026 ± 0.015 mg/kg) (**Figure 2B**). The presence of Cd at elevated levels in certain areas suggests potential industrial or vehicular sources of contamination.

Iron (Fe) concentrations varied between 156.57 mg/kg and 169.83 mg/kg, with the highest levels at Sunset Point (169.83 ± 10.70 mg/kg) and Gurusikhar (169.49 ± 18.98 mg/kg). The lowest levels were found at Oriya Road (156.57 ± 24.13 mg/kg) and Nakki Lake Road (157.42 ± 29.10 mg/kg) (**Figure 2C**). The higher Fe concentrations in urban areas might reflect increased vehicular wear and tear.

Lead (Pb) concentrations ranged from 0.994 mg/kg to 1.119 mg/kg, with the highest levels at Nakki Lake Road (1.119 ± 0.225 mg/kg) and Gurusikhar (1.039 ± 0.205 mg/kg). The lowest Pb levels were observed at Sunset Point (0.994 ± 0.395 mg/kg) and Oriya Road (1.009 ± 0.323 mg/kg) (**Figure 2D**). The elevated Pb concentrations highlight significant pollution sources, possibly related to traffic emissions.

Zinc (Zn) levels ranged from 15.10 mg/kg to 21.12 mg/kg, with the highest concentrations observed at Nakki Lake Road (21.12 ± 2.77 mg/kg) and Oriya Road (19.78 ± 8.04 mg/kg). The lowest levels were recorded at Sunset Point (15.10 ± 2.65 mg/kg) and Gurusikhar (17.89 ± 7.02 mg/kg) (**Figure 2E**). Zn levels are relatively higher in urban settings, which could be attributed to various sources, including industrial emissions.

Nickel (Ni) concentrations varied from 0.560 mg g^{-1} to 0.790 mg/kg, with higher levels at Nakki Lake Road (0.790 ± 0.204 mg/kg) and Oriya Road (0.666 ± 0.225 mg/kg). The lowest levels were found at Sunset Point (0.560 ± 0.150 mg/kg) and Gurusikhar (0.629 ± 0.143 mg/kg) (**Figure 2F**). Elevated Ni levels could indicate vehicular emissions or industrial pollution.

Overall, the variation in metal concentrations across different locations highlights the effectiveness of *P. hispidula* as bioindicator for PTEs pollution. The data underscores the need for continued monitoring and mitigation efforts to address environmental pollution and protect both environmental and public health.

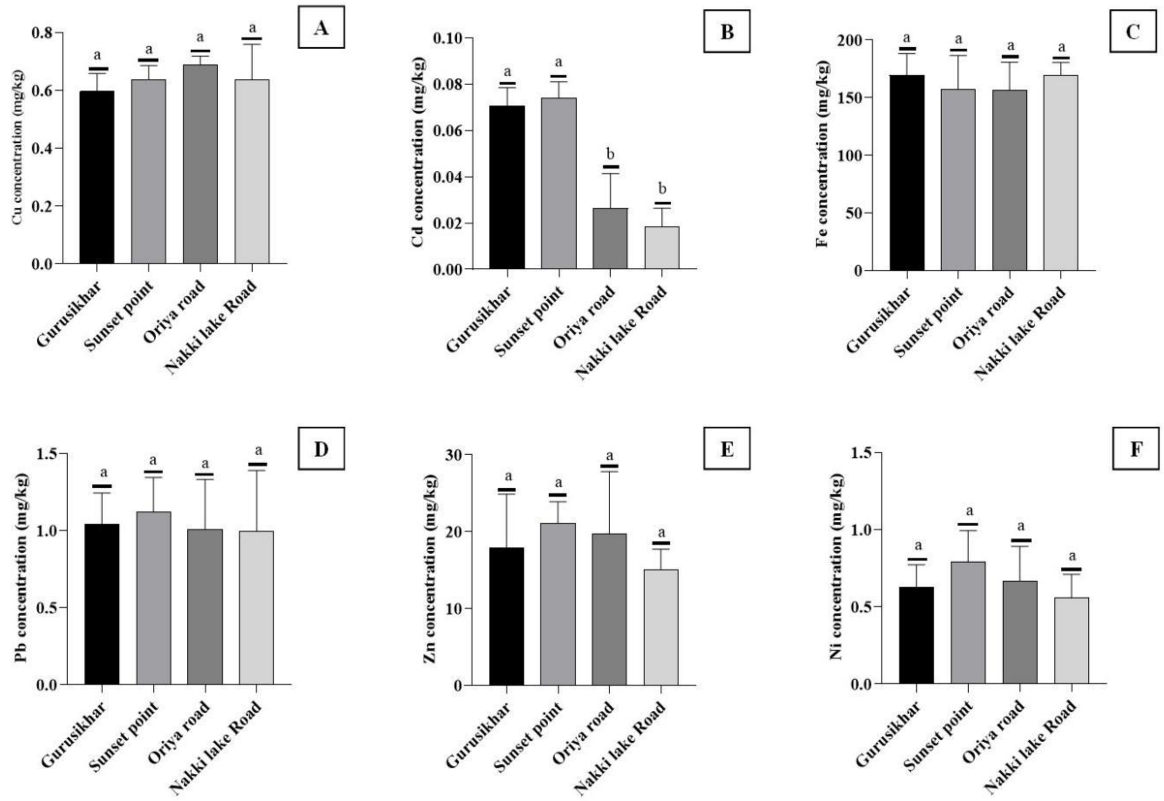

Figure 2: PTEs concentrations (mg/kg, dw) at four locations in Mount Abu. Bar graphs showing concentrations of (A) Cu, (B) Cd, (C) Fe, (D) Pb, (E) Zn, and (F) Ni measured in mg/kg at four different locations. Values represent means ± standard deviation. Different letters above bars indicate statistically significant differences between locations ($p < 0.05$).

Table 3: PTEs concentrations at four different locations in the Mount Abu region. Data represents mean ± standard deviation values for PTEs concentrations, including Zn, Pb, Ni, Cu, and Fe (n=3, expressed in mg/kg dry weight).

Parameter	Gurusikhar	Nakki Lake Road	Oriya Road	Sunset Point
Zinc	17.89 ± 7.02	21.12 ± 2.77	19.78 ± 8.04	15.10 ± 2.65
Lead	1.039 ± 0.205	1.119 ± 0.225	1.009 ± 0.323	0.994 ± 0.395
Nickel	0.629 ± 0.143	0.790 ± 0.204	0.666 ± 0.225	0.560 ± 0.150

Parameter	Gurusikhar	Nakki Lake Road	Oriya Road	Sunset Point
Copper	0.596 ± 0.062	0.638 ± 0.048	0.690 ± 0.028	0.638 ± 0.121
Cadmium	0.071 ± 0.008	0.074 ± 0.007	0.026 ± 0.015	0.018 ± 0.008
Iron	169.49 ± 18.98	157.42 ± 29.10	156.57 ± 24.13	169.83 ± 10.70

Correlation Analysis

The correlation matrix elucidates the interactions between photosynthetic pigments and PTEs across four distinct locations: Gurusikhar, Nakki Lake Road, Oriya Road, and Sunset Point. Strong positive correlations were observed among photosynthetic pigments, with chl *a* and chl *b* showing a robust relationship (r = 0.92), alongside chl *a* with total chl (r = 0.96) and chl *b* with total chl (r = 0.96). Carotenoids exhibited significant positive correlations with chl *a* (r = 0.86), chl *b* (r = 0.68), and total chl (r = 0.83), reflecting their interconnected roles in photosynthesis.

Among PTEs, Zn and Ni displayed a strong positive correlation (r = 0.81), particularly at Nakki Lake Road and Oriya Road, where higher concentrations were noted, suggesting shared environmental sources or uptake mechanisms. A moderate correlation was found between Cd and Ni (r = 0.55).

Strong negative correlations indicate PTEs stress on photosynthetic pigments. Chl *a* showed negative correlations with Cd (r = -0.69) and Ni (r = -0.50), indicating that Cd and Ni accumulation, particularly at Oriya Road where Cd peaked, inhibits chlorophyll biosynthesis. Similarly, other chlorophyll parameters demonstrated inverse relationships with various PTEs, reflecting the detrimental effects of metal contamination on photosynthetic processes.

Weak or negligible correlations were observed for some parameters, including carotenoid vs. Fe (r = -0.024) and Pb vs. Cd (r ≈ 0), suggesting site-specific variations without consistent patterns across the study sites.

Environmentally, the strong clustering of chlorophylls and carotenoids at Sunset Point and Gurusikhar indicates favorable conditions for photosynthesis, likely due to lower pollution levels. In contrast, negative correlations between pigments and PTEs at Nakki Lake Road and Oriya Road reflect anthropogenic heavy metal stress, reducing chlorophyll content and impairing photosynthetic efficiency.

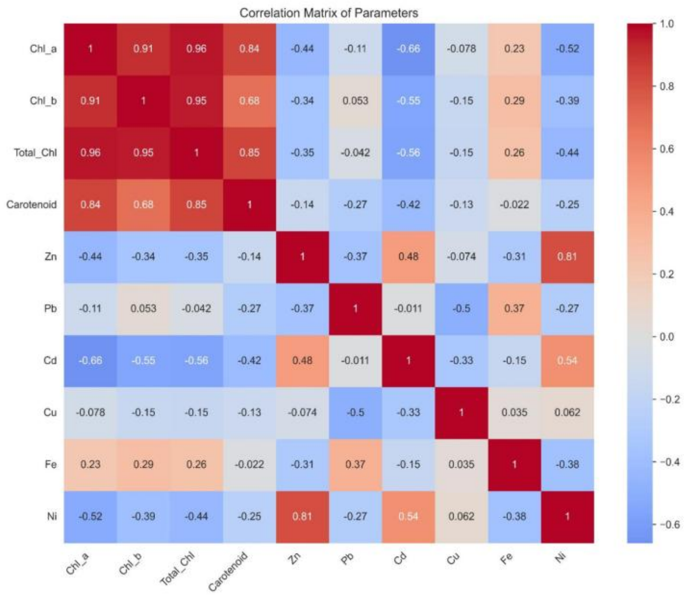

Figure 3: Correlation matrix of photosynthetic pigments (chl *a*, chl *b*, total chl, carotenoid) and PTEs (Zn, Pb, Cd, Cu, Fe, Ni). The heatmap displays Pearson's correlation coefficients, where values range from -1 to +1. Strong positive correlations are shown in deep red (e.g., chl *a* vs total chl, r = 0.96; Zn vs Ni, r = 0.81), indicating that these parameters increase together. Strong negative correlations are shown in deep blue (e.g., chl *a* vs Cd, r = -0.69; chl *a* vs Ni, r = -0.50), reflecting an inverse relationship. Weak or insignificant correlations (values near 0, shown in pale colors) suggest little or no linear association (e.g., carotenoid vs Fe, r = -0.024).

DISCUSSION

In the present study, chl *a* level varied from 0.108 to 0.244 mg g^{-1} fresh weight, chl *b* from 0.062 to 0.117 mg g^{-1}, and total chlorophyll from 0.169 to 0.343 mg g^{-1} (**Figure 1A, B, C**). Lower chlorophyll levels at highly polluted locations like Nakki Lake Road and Oriya Road demonstrate pollution's negative effect on chlorophyll production. Our research corroborates that elevated PTEs concentrations are associated with reduced chlorophyll content, aligning with previous studies demonstrating PTEs affect on photosynthetic pigments and respiratory enzymes (Shukla and Upreti, 2007b; Bajpai *et al.,* 2009; Shukla *et al.,* 2012; 2014; Thakur *et al.,* 2024). This also corresponds with studies indicating inconsistent outcomes regarding vehicular activity and urban pollution impacts on photosynthetic pigments (Bajpai *et al.,* 2009; Wakefield and Bhattacharjee, 2011; Sujetoviene and Sliumpaite, 2013). Distance and direction from pollution sources, height above ground, exposure duration, and sample size affect chlorophyll depletion (Boonpragob and Nash III, 1991; Carreras *et al.,* 1998; Shukla *et al.,* 2012).

Carotenoid concentrations ranged from 0.103 to 0.173 mg g^{-1} FW (**Figure 1D**), with elevated levels in contaminated areas suggesting defensive reactions to PTEs pollution. These results align with research demonstrating carotenoids prevent photooxidative adverse effects in lichens (Bačkor and Loppi, 2009; Shukla and Upreti, 2007b; Kardish *et al.,* 1987; Bajpai *et al.,* 2009).

Our study revealed high PTEs levels at Nakki Lake Road and Oriya Road due to heavy vehicle traffic and industrial operations (**Figure 2, Table 3**), while Sunset Point showed lower concentrations due to less polluted surroundings. PTEs accumulation in *P. hispidula* varies with environmental contamination levels, corresponding with studies showing industrial processes and vehicle emissions raise PTEs levels via fuel additives and engine wear (Bajpai *et al.,* 2010; 2014; Loppi, 2019).

Copper (Cu) accumulation showed concentration-dependent effects on lichen health, being necessary in minimal quantities but toxic at elevated levels (Gupta *et al.,* 2024; Rola *et al.,* 2019; Baptista *et al.,* 2008; Osyczka and Rola, 2019).

Cadmium (Cd) accumulation demonstrated significant bioaccumulation potential at polluted sites. Cd sources include both natural and anthropogenic activities like mining, fossil fuel burning, and cement production (Shukla *et al.,* 2012; Nimis *et al.,* 1990; Bajpai *et al.,* 2011). Iron (Fe) accumulation was particularly notable near roadways, aligning with studies showing Fe presence in atmospheric dust from combustion and traffic (Gupta *et al.,* 2017; Singh *et al.,* 2018; Rani *et al.,* 2011; Gupta *et al.,* 2024).

Lead (Pb) concentrations showed significant variation across locations, with higher levels at traffic-dense areas causing visible lichen impacts. These findings correlate with research showing Pb exposure causes lichen deterioration and structural weakening (Pacyna and Pacyna, 2001; Chetia *et al.,* 2021; Chahloul *et al.,* 2022; Loppi 2019).

Zinc (Zn) concentrations showed significant accumulation impacting metabolic processes at polluted sites, corresponding with research demonstrating Zn damages lichen cells and reduces biodiversity (Ward, 1990; Shukla *et al.,* 2006; Shukla and Upreti, 2012; Bajpai *et al.,* 2009; Shukla and Upreti, 2007a).

Nickel (Ni) levels were elevated near high-traffic areas, correlating with reduced lichen vitality, aligning with studies showing Ni emissions harm photosynthesis and reduce biodiversity (Kumari, 2019; Monaci *et al.,* 2000; Rola *et al.,* 2019).

Correlation analysis revealed significant relationships among photosynthetic pigments and PTEs across study locations (**Figure 3**). Strong positive correlations were observed among photosynthetic pigments: chl *a* and chl *b* ($r = 0.92$), chl *a* with total chl ($r = 0.96$), and chl *b* with total chl ($r = 0.96$). Carotenoids showed significant correlations with chl *a* ($r = 0.86$), chl *b* ($r = 0.68$), and total chl ($r = 0.83$), reflecting interconnected photosynthetic roles. Among PTEs, Zn and Ni displayed strong positive correlation ($r = 0.81$), particularly at Nakki Lake and Oriya Road, suggesting shared environmental sources. Moderate correlation was found between Cd and Ni ($r = 0.55$). Strong negative correlations indicated PTEs stress on photosynthetic pigments, with chl *a* showing negative correlation with Cd ($r = -0.69$) and Ni ($r = -0.50$), indicating that Cd and Ni accumulation inhibits chlorophyll biosynthesis. Weak correlations were observed for carotenoid vs. Fe ($r = -0.024$) and Pb vs. Cd ($r \approx 0$), suggesting site-specific variations.

Our findings demonstrate PTEs pollution significantly harms lichens, highlighting industrial and urban environmental issues. Strong clustering of chlorophylls and carotenoids at Sunset Point and Gurusikhar indicates favourable photosynthetic conditions due to lower pollution levels. Conversely, negative correlations between pigments and PTEs at Nakki Lake Road and Oriya Road reflect anthropogenic stress, reducing chlorophyll content and impairing photosynthetic efficiency. These results emphasize lichens' effectiveness as bioindicators for air quality assessment.

Traffic congestion represents a major pollution source in Mount Abu, especially around Nakki Lake Road and Oriya Road. Vehicle emissions, combined with small-scale industries, workshops, commercial operations, construction activities, and unpaved roads contributing to PTEs contamination through dust generation. These factors create densely contaminated metropolitan areas, stressing the necessity for comprehensive pollution mitigation techniques and regular monitoring to manage urban and industrial air quality impacts.

CONCLUSION

The present study suggest that *Phaeophyscia hispidula* is an effective air quality biomonitor in Mount Abu's at various environmental gradients, as it has acquired various PTEs from all sites. The spatial variation study showed Nakki Lake road was the most polluted and Sunset Point the moderately cleanest, correlated with anthropogenic activities and vehicle traffic. PTEs concentrations showed inverse correlations with chlorophyll and carotenoid levels in *P. hispidula*, with highest metal accumulation at Nakki Lake Road and Oriya Road corresponding to lowest pigment concentrations.

The study provides baseline environmental data for Mount Abu's hill station ecosystem, filling a significant gap in Rajasthan's lichen biomonitoring research. For developing regions without advanced monitoring equipment, the technique provides a cost-effective option for continuous air quality assessment.

These findings provide crucial scientific information for mountain tourism destination environmental strategy and pollution control. To preserve Mount Abu's natural integrity, the pollution gradient highlights the necessity for preventative measures in low-contamination areas and strict regulations in high-impact zones.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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