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Assessing edaphic factors of the habitat of the endemic pitcher plant (*Nepenthes khasiana*) in Meghalaya, India

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Abstract

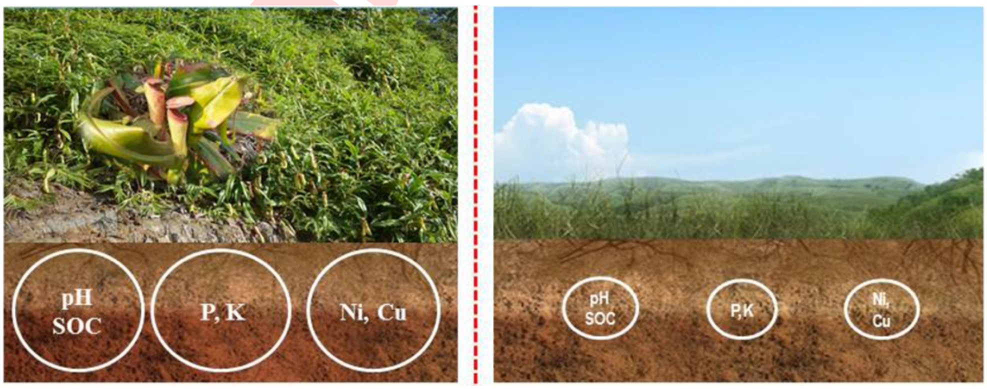
Aim: *Nepenthes khasiana*, an endemic and endangered carnivorous plant of North-east India, is largely confined to Meghalaya. Recognising the pivotal role of edaphic factors in determining plant distribution, the present study aimed to identify the key edaphic factors and heavy metals influencing the soil in pitcher plant-thriving areas of the Garo, Khasi, and Jaintia Hills of Meghalaya.

Methodology: Soil samples were collected from pitcher plant sites and adjacent control areas (~200 m away). Five locations per hill region were randomly selected, and ten samples were collected per location, yielding a total of 150 samples. Soil physico-chemical properties and heavy metal concentrations were analysed using standard methods. Seasonal sampling could not be conducted due to difficult terrain and weather conditions.

Results: Significant differences were observed in soil moisture, available nitrogen, and concentrations of copper, iron, manganese, and nickel (F=5.796-55.534). Correlation analysis revealed that soil moisture was strongly associated with organic carbon (r=0.666), available nitrogen (r=0.961), available potash (r=0.832), and zinc (r=0.639). Principal Component Analysis identified soil pH, organic carbon, available phosphorus, potash, nickel, and copper as major contributors influencing pitcher plant habitats.

Interpretation: Soil supporting *N. khasiana* were more acidic and enriched in organic carbon, phosphorus, and potash than adjacent areas, with the Jaintia Hills showing the highest nutrient levels. Overall, the soil quality, particularly nutrients and micronutrients, plays a crucial role in the conservation and management of this species.

Key words: Carnivorous plants, Edaphic factors, *Nepenthes khasiana,* Pitcher plant, Sustainable management



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Introduction

Worldwide, approximately 810 species of carnivorous plants are distributed across North America, South Asia, and Australia (Adamec *et al.,* 2021). India harbours about 44 carnivorous plant species belonging to the families *Droseraceae* (*Drosera:* 3; *Aldrovanda:* 1), *Lentibulariaceae* (*Utricularia:* 38; Pinguicula: 1), and *Nepenthaceae,* represented by a single pitcher plant species (Santapau and Henry, 1976; Kamble *et al.,* 2012). North-east India accounts for nearly half of this diversity, with 21 species reported (Verma *et al.,* 2014). *Nepenthes khasiana* Hook. f. is the only pitcher plant species endemic to India and is found exclusively in the Indo-Burma biodiversity hotspot (Mao and Kharbuli, 2002). Its distribution is confined to fragmented forest patches in all three hills of Meghalaya, mostly in the Jaintia and Garo Hills (Bhattacharya *et al.,* 2024). Due to habitat loss, overexploitation and restricted distribution, *N. khasiana* is listed as Endangered in the IUCN Red Data Book (Ved *et al.,* 2015), included under Appendix I of CITES (CITES-UNEP, 2022) and placed on the Government of India's Negative List of Export (Ziemer, 2010).

Soil, comprising unconsolidated minerals and organic matter, serves as a primary medium for plant growth and ecosystem functioning (Haliru *et al.,* 2014). In tropical ecosystems, plant diversity and composition are shaped by a combination of abiotic factors such as soil type, nutrients, physico-chemical properties, heavy metals and biotic interactions (Arruda *et al.,* 2015). Nutrient cycling within the soil-plant system is dynamic, involving nutrient uptake by plants and their return through litter fall and root turnover, mediated by microbial processes (Nair, 1999). Consequently, soil properties play a critical role in determining vegetation patterns at regional and global scales (Becknell and Powers, 2014). Distribution of *Nepenthes* species is primarily influenced by climatic factors such as altitude, humidity, rainfall, and light intensity (Clarke and Moran, 2016; Rawi and Shahrudin, 2021). Although often regarded as thriving in nutrient-poor environments, *Nepenthes* species typically prefer open canopies, high soil moisture, and mildly acidic, well-aerated soils, sometimes occurring in disturbed habitats (Sim *et al.,* 1992; Ellison and Gotelli, 2002). *N. khasiana* commonly grows on sandy soils and rocky or cliff substrates under high humidity and frequent rainfall.

Previous studies have examined the physico-chemical properties of soil and heavy metal accumulation in *Nepenthes habitats,* including mining-affected areas (Rahim *et al.,* 2007; Hidayat *et al.,* 2018; Mansur *et al.,* 2024). However, most studies have focused solely on soil within *Nepenthes*-inhabited zones, with limited comparison to adjacent non-inhabited areas, and rarely employ multivariate statistical approaches. Therefore, comparative studies evaluating the soil physico-chemical properties of soil and heavy metal concentrations in both pitcher plant-inhabiting (near) and non-inhabiting (far) areas across the Garo, Khasi, and Jaintia Hills are lacking. In light of the above, the present study aimed to address this gap by identifying key edaphic factors associated with the distribution of *N. khasiana* using multivariate statistical analyses, thereby providing insights essential for its conservation and sustainable management.

Materials and Methods

Study area: The study was conducted in the Meghalaya state of India, located between 24º 58'N and 26º 07'N latitude and 89º 48'E and 92º 51'E longitude (Fig. 1). The total area enclosed by the state is 22,429 sq. km, and the total forest area is 8,510 sq. km. The various types of forests, like tropical moist and dry deciduous forests, tropical evergreen forests, tropical semi-evergreen forests, grasslands and savannas, temperate forests, and sacred groves found in Meghalaya, provide habitation to a large variety of mammals, birds, and plants. The western part of the northeastern state receives an average annual rainfall of around 2600 mm, while the annual rainfall is between 2500 and 3000 mm in northern Meghalaya. However, the southeastern Meghalaya receives annual showers of above 4000 mm (Dikshit and Dikshit, 2014). Garos, Khasis, and Jaintia are the major inhabitants of the state of Meghalaya.

Soil sampling: Soil samples were randomly collected from the Garo, Khasi, and Jaintia Hills from both pitcher plant-inhabited areas (near areas) and adjacent non-inhabited control sites (far areas) located approximately 200 m away. This distance was maintained to minimize the influence of the pitcher plant rhizosphere while ensuring similar macro-environmental conditions. Sampling was conducted from the topsoil layer (0–15 cm) using a composite sampling approach, as pitcher plant roots are primarily superficial. In each hill region, five locations were randomly selected, and ten samples were collected per location, five from near areas and five from far areas, resulting in a total of 150 soil samples.

Soil analyses: Soil samples were air-dried and sieved through 2.0 mm and 0.5 mm meshes. Samples passing through 2.0 mm were used for physical analyses, while those passing through 0.5 mm were used for chemical analyses. All processed samples were stored in labelled airtight containers for laboratory analysis. Soil texture was determined using the International Pipette Method (Piper, 1966). Soil pH was measured in a 1:2 (w/v) soil–water suspension using a digital pH meter (Jackson, 1967). Soil moisture (SM) content was determined gravimetrically by oven-drying samples at 105 °C for 24 hr (Topp, 1993). Soil organic carbon (SOC) was estimated by the modified Walkley– Black wet oxidation method (Walkley and Black, 1934). Soil available nitrogen (SAN), phosphorus (SAP), and potassium (SAK) were determined using standard methods: alkaline potassium permanganate for nitrogen (Subbiah and Asija, 1956), Bray's extraction and colourimetric method for phosphorus (Dickman and Bray, 1940), and neutral ammonium acetate extraction followed by flame photometry for potassium (Hanway and Heidal, 1952). Micronutrients (Zn, Cu, Fe, Ni, and Mn) were extracted using the DTPA method and quantified using atomic absorption spectrophotometry (Lindsay and Norvell, 1978). Lead and nickel

Table 1: Comparative analysis of different soil parameters in the near pitcher plant areas of Garo, Khasi and Jaintia Hills, Meghalaya

Parameters	Garo hill	Khasi hill	Jaintia hill	F-test (df=2, 72)
pH	4.776±0.43	4.744±0.31	5.027±0.52	0.657
SM (%)	7.572±1.11^a	7.712±2.10^a	36.270±17.05^b	13.821*
SOC (%)	1.329±1.10	1.051±0.38	2.730±3.05	1.141
SAN (kg ha^{-1})	28.500±5.80^a	32.100±7.15^a	377.674±173.16^b	20.071*
SAP (kg ha^{-1})	29.412±9.15	39.962±11.39	41.090±8.24	2.2z16
SAK (kg ha^{-1})	172.996±36.41	175.898±43.79	268.500±139.74	1.944
Zn (mg kg^{-1})	1.452±0.42	1.686±0.40	1.911±0.98	0.606
Cu (mg kg^{-1})	1.561±0.53^a	2.221±0.30^b	0.633±0.23^c	22.737*
Fe (mg kg^{-1})	147.610±7.13^a	41.745±5.05^a	151.514±47.26^b	25.213*
Mn (mg kg^{-1})	27.111±3.73^a	29.764±1.95^a	7.932±4.54^b	55.534*
Ni (mg kg^{-1})	0.550±0.24^a	1.049±0.42^b	0.288±0.40^a	5.796*
Pb (mg kg^{-1})	1.033±0.44	1.132±0.39	2.753±2.40	2.297

Values are mean ± S.D; * p<0.05. Values in the same row with different alphabets are significantly different by LSD. SM: Soil moisture, SOC: Soil organic carbon, SAN: Soil available nitrogen, SAP: Soil available phosphorus, SAK: Soil available potash

concentrations were measured using EDTA extraction followed by AAS analysis (Ding *et al.,* 2013). The Soil Nutrient Index (SNI) was calculated by the formula given by Parker *et al.* (1951).

$$\text{Nutrient Index} = (N_1 \times 1 + N_2 \times 2 + N_3 \times 3)/NT$$

Where N_1, N_2, and N_3 are the numbers of samples in low (<1.67), medium (1.67–2.33), and high (>2.33) nutrient classes, respectively (Ramamoorthy and Bajaj, 1969), and NT is the total number of samples analysed.

Statistical analyses: Data normality was tested using the Shapiro-Wilk test, and non-normal variables were log-transformed. Comparative analyses were performed using Student's t-test, F-test, and Chi-square test (p<0.05), with LSD for post hoc comparisons. Multivariate analyses, including Pearson's correlation, hierarchical cluster analysis (HCA), principal component analysis (PCA), and linear mixed-effects modelling (LMM), were applied to identify the key soil determinants influencing *N. khasiana* distribution using XLSTAT and SPSS v25.

Results and Discussion

The Shapiro-Wilk test indicated that several soil parameters (near areas: pH, SOC, SAP, SAK, Zn and Cu; far areas: pH, SOC, SAP, SAK, Zn, Cu and Ni) followed a normal distribution (p>0.05), whereas others (near areas: SM, SAN, Fe, Mn, Ni and Pb; far areas: SM, SAN, Fe, Mn, and Pb) showed significant deviation from normality (p<0.05). Log transformation was applied the non-normally distributed variables, which subsequently met the assumption of normality. Therefore, parametric tests were employed for further statistical analyses.

Across all the study regions in the Garo, Khasi and Jaintia Hills, the soil texture was consistently classified as sandy clay loam, regardless of proximity to *N. khasiana* habitats (near areas) or non-inhabiting areas (far areas). Soil pH was uniformly acidic across all sites in the Garo, Khasi, and Jaintia Hills. However, several chemical parameters showed statistically significant variation between near and far areas. This included pH, SM, SAN, SAP, SAK, Fe, and Mn content, as determined by t-test and Chi-squared analyses. Other parameters like SM, Zn, Cu, Ni and Pb showed site-specific variations. SM content varied significantly across the near areas of three hills (F=13.821, p<0.05), with post hoc least significant difference (LSD) tests indicating that the Jaintia Hills exhibited significantly higher moisture levels compared to both Garo and Khasi Hills. Although soils from the Jaintia Hills showed higher SOC content than those from the Garo and Khasi Hills, the differences were not statistically significant (p>0.05). SAN content differed significantly among the hills (F=20.071, p<0.05), with the Jaintia Hills significantly differing from both the Garo Hills and Khasi Hills. Cu concentrations also showed significant variation (F=22.737, p<0.05), and the LSD tests confirmed significant pairwise differences among all three locations. Similarly, Fe and Mn concentrations varied significantly among the sites (Fe: F=25.213; Mn: F=55.534, p<0.05), with Jaintia soils recording the highest levels of both elements. Ni also exhibited statistically significant variation (F=5.796, p<0.05), with significant differences observed between Khasi-Garo and Khasi-Jaintia. Pb, SAP, SAK, and Zn did not show significant differences across the hills. Overall, Jaintia Hills exhibited greater concentrations of most soil nutrients, except for Cu, Mn, and Ni, highlighting its comparatively nutrient-rich soils (Table 1; Fig. 2).

SNI was calculated for soil pH, SOC, SAN, SAP and SAK to evaluate the fertility status of *N. khasiana* habitats across the near areas of Garo, Khasi and Jaintia Hills. The results indicated distinct fertility levels for each parameter and site. In the near areas of Garo Hills, the soil exhibited low pH (SNI = 1.0), high SOC (2.8), low SAN (1.0), medium SAP (2.0), and medium SAK (2.0). In the Khasi Hills, the near areas' soil showed low pH (1.0), high SOC (2.4), low SAN (1.0), medium SAP (1.8), and medium SAK (1.8). Soils from the near areas of Jaintia Hills were also low in pH (1.0), however showed high SOC (2.8), medium SAN (2.0),

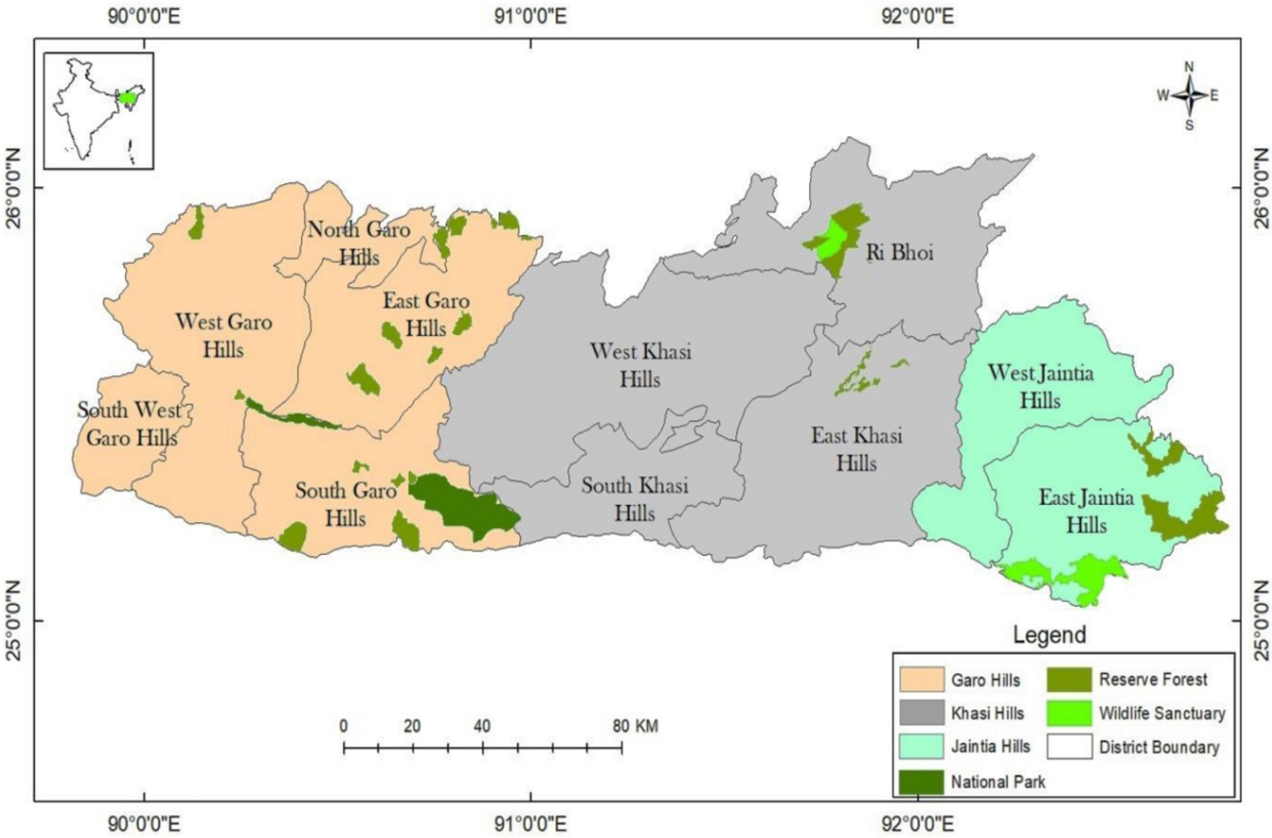

Fig. 1: Map of Meghalaya, India, showing the different hills where this study was conducted.

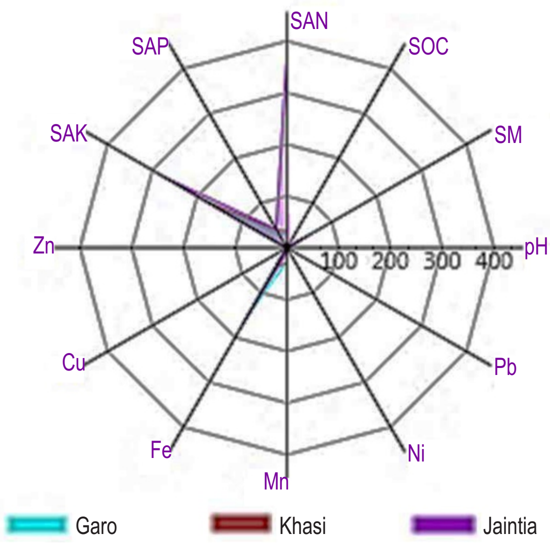

Fig. 2: Comparative analysis of soil physico-chemical factors among the three hills. SM: Soil moisture, SOC: Soil organic carbon, SAN: Soil available nitrogen, SAP: Soil available phosphorus, SAK: Soil available potash.

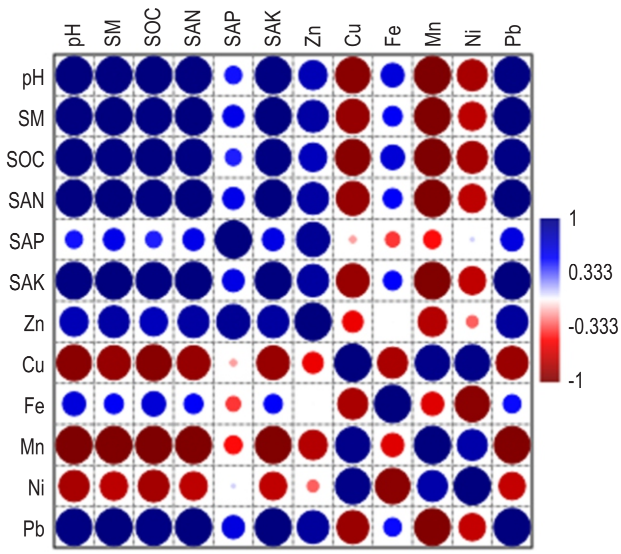

Fig. 3: Correlation analysis among different soil samples of the near area in Garo, Khasi, and Jaintia Hills of Meghalaya. SM: Soil moisture, SOC: Soil organic carbon, SAN: Soil available nitrogen, SAP: Soil available phosphorus, SAK: Soil available potash.

Table 2: Correlation analysis of different soil parameters of near and far pitcher plant areas under the study of all three hills in Meghalaya

Parameters	pH	SM	SOC	SAN	SAP	SAK	Zn	Cu	Fe	Mn	Ni	Pb
pH	1											
SM	0.268	1										
SOC	-0.107	0.666**	1									
SAN	0.232	0.961**	0.739**	1								
SAP	0.127	0.278	-0.059	0.224	1							
SAK	0.023	0.832**	0.731**	0.800**	0.026	1						
Zn	0.027	0.639*	0.775**	0.595*	0.075	0.630*	1					
Cu	-0.117	-0.610*	-0.296	-0.667**	-0.188	-0.294	-0.049	1				
Fe	-0.335	0.197	-0.096	0.142	0.249	0.131	-0.068	-0.471	1			
Mn	-0.434	-0.794**	-0.433	-0.872**	-0.229	-0.524*	-0.195	0.802**	-0.142	1		
Ni	-0.363	-0.238	0.143	-0.256	-0.310	0.200	0.195	0.660**	-0.319	0.533*	1	
Pb	0.674**	0.512	-0.191	0.365	0.348	0.213	0.077	-0.324	0.107	-0.436	-0.395	1

SM: Soil moisture, SOC: Soil organic carbon, SAN: Soil available nitrogen, SAP: Soil available phosphorus, SAK: Soil available potash

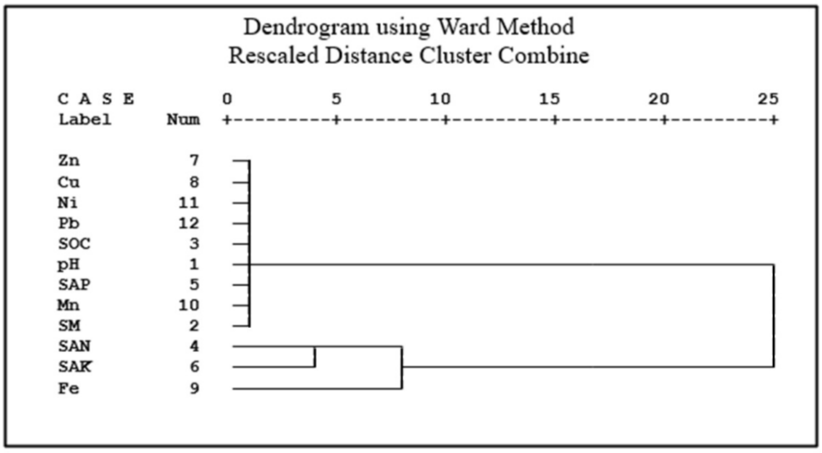

Fig. 4: Cluster analysis of the near area in Garo, Khasi, and Jaintia Hills, Meghalaya. SM: Soil moisture (%), SOC: Soil organic carbon (%), SAN: Soil available nitrogen (kg/ha), SAP: Soil available phosphorus (kg ha^{-1}), SAK: Soil available potash (kg ha^{-1}), Zn, Cu, Fe, Mn, Ni, and Pb (mg kg^{-1}).

medium SAP (2.0), and high SAK (2.4). Overall, soils across all near areas were consistently acidic and low in SAN, while exhibiting high levels of SOC and moderate to high availability of SAP and SAK. These findings suggest that *N. khasiana* tend to inhabit nutrient-enriched, but nitrogen-limited acidic soils, with elevated levels of organic matter and select macronutrients.

Significant correlations among soil variables were observed across the three hill regions, indicating potential interaction between soil nutrients and trace metals relevant to the edaphic conditions of *N. khasiana* habitats. In the Garo Hills, a strong negative correlation was found between SAP and Cu ($r=-0.898$, $p<0.05$). In the Khasi Hills, the soil pH was negatively correlated with SAK ($r=-0.956$, $p<0.05$), and SAP exhibited a negative correlation with Mn ($r=-0.905$, $p<0.05$). A strong positive association was also observed between Fe and Ni ($r=0.916$, $p<0.05$). In the Jaintia Hills, SOC showed a strong positive correlation with SAN ($r=0.943$, $p<0.05$) and Ni ($r=0.972$, $p<0.05$). SAN was also positively correlated with SAK ($r=0.944$, $p<0.05$), Zn ($r=0.931$, $p<0.05$), and Ni ($r=0.947$, $p<0.05$).

In combining the data of all three hills, the SM content exhibited significant positive correlations with SOC ($r=0.666$, $p<0.05$), SAN ($r= 0.961$, $p<0.05$), SAK ($r=0.832$, $p<0.05$) and Zn ($r=0.639$, $p<0.05$), and significant negative correlations with Cu ($r=-0.610$, $p<0.05$) and Mn ($r=-0.794$, $p<0.05$). Additionally, the pH was positively correlated with Pb ($r=0.674$, $p<0.05$), and SOC was significantly associated with SAN, SAK and Zn (Table 2; Fig. 3). These patterns indicate that the soils supporting *N. khasiana* exhibit coordinated variation in macronutrient availability and trace metal concentrations, which may reflect the underlying biogeochemical linkages in these ecosystems.

HCA revealed distinct groupings of associated soil parameters within each hill, reflecting underlying patterns of nutrient and metal co-variation in *N. khasiana* habitats. In the

Garo Hills, two major clusters were identified: Cluster 1 comprised Zn, Cu, SOC, Ni, Pb, pH, SM, SAN, Mn and SAP; Cluster 2 included SAK and Fe. For Khasi Hills, Cluster 1 grouped SOC, Ni, Pb, Zn, Cu, pH and SM, while Cluster 2 consisted of SAN, Mn, Fe and SAP. Similarly, the Jaintia Hills exhibited a primary cluster consisting of Cu, Ni, Zn, SOC, pH, Pb, Mn, SM and SAP, with SAN and SAK forming the second cluster. When data from all three hills were analysed collectively, Cluster 1 included Zn, Cu, Ni, Pb, SOC, pH, SAP, Mn and SM whereas Cluster 2 comprised SAN and SAK. These consistent clustering patterns across individual and combined hill datasets suggest a strong co-association of micronutrients (Zn, Cu, Ni, Pb and Mn) with SOC and SM, highlighting the role of integrated nutrient-metal dynamics in shaping the edaphic conditions of *N. khasiana* habitats (Fig. 4). PCA showed that edaphic variability in *N. khasiana* habitats differed across regions. In Garo Hills, three components (93.199%) were mainly influenced by SM (0.916), SAK (0.879), Pb (0.706), Ni (0.606), Cu (0.976), SAN (0.511), and pH (0.941). In the Khasi Hills, four components (100%) were dominated by SAK (0.951), Fe (0.802), SAN (0.755), Mn (0.909), Ni (0.790), SM (0.998), SOC (0.665), Cu (0.866), and Pb (0.898). In Jaintia Hills, four components (100%) showed strong loadings for Zn (0.988), SAK (0.970), SAN (0.968), SM (0.962), Ni (0.926), SOC (0.885), pH (0.962), Pb (0.862), Fe (0.990), and SAP (0.955). For the combined dataset from all three hills, four principal components explained 86.720% of the total variance. PC1 (34.610%) showed strong loadings for SOC (0.905) and SAK (0.906), while PC2 (23.877%) was associated with Cu (0.921) and Ni (0.809). PC3 (16.262%) revealed a strong relationship between pH (0.938) and Pb (0.701), and PC4 (11.971%) was defined by SAP (0.847) and Fe (0.541).

These results highlight the importance of SOC, SAK, pH, Cu, Ni, SAP and Fe as key edaphic variables across pitcher plant habitats in Meghalaya. Overall, the PCA revealed that soil fertility and trace metal interactions, particularly involving SM, SOC, SAK, SAN, pH and selected heavy metals (Cu, Ni, Pb, Fe, Zn and Mn), are central to defining the ecological characteristics of *N. khasiana* environments across three hill regions (Tables 3 and 4). LMM results (Table 5) showed that SAN and SAK were significant predictors of soil physico-chemical variation in *Nepenthes* inhabiting areas. These parameters may influence the nutrient cycling and habitat suitability across the studied sites in Meghalaya. This study aimed to compare the soil characteristics of wild *N. khasiana* habitats with adjacent non-inhabiting (far) areas, examine interrelationships among soil variables, and identify key edaphic drivers influencing the species' distribution in Meghalaya. Soil is a primary reservoir of nutrients, and water plays a major role in determining plant distribution and vegetation structure worldwide (Mangosongo *et al.,* 2019). Among soil physico-chemical properties, soil type is a critical determinant of habitat variation and plant assemblages (Xiao *et al.,* 2023). *Nepenthes* species commonly occupy loamy to sandy soils (Rawi and Shahrudin, 2021), and in the present study, both pitcher plant (near) and control (far) areas across the Garo, Khasi and Jaintia Hills were characterised by sandy clay loam soils, which is consistent with the previous reports from Meghalaya (Das *et al.,* 2014; Sen *et al.,* 2017). Soil pH, often regarded as the "master variable", strongly influences nutrient availability, microbial activity, and plant growth (Minasny *et al.,* 2016). While higher pH enhances macronutrient availability, acidic conditions favour the solubility of several micronutrients (Finck, 1976).

Soil pH, often regarded as the "master variable", strongly influences nutrient availability, microbial activity, and plant growth (Minasny *et al.,* 2016). While higher pH enhances macronutrient availability, acidic conditions favour the solubility of several micronutrients (Finck, 1976). *Nepenthes* habitat elsewhere is typically highly acidic, with reported pH values ranging from 3.4 to 5.5 (Hidayat *et al.,* 2018; Rawi and Shahrudin, 2021; Setiawan *et al.,* 2025). In contrast, the soils in Meghalaya were moderately acidic, with pH ranging from 4.2–5.07 in near areas and 4.15–5.13 in far areas. North-east India is known for acidic soils due to high rainfall, leaching and parent material (Saha *et al.,* 2012). The slightly higher mean pH in near areas compared to far areas demonstrate a buffering effect linked to higher soil organic carbon under *N. khasiana* vegetation. SM is another critical factor influencing nutrient uptake, plant growth and soil fertility (Kekane *et al.,* 2015; Parmar, 2016). SM was significantly higher in the Jaintia Hills than in the Garo and Khasi Hills, reflecting regional differences in rainfall, topography, and vegetation cover. Although moisture levels were lower than those reported from tropical peat swamps (Rawi and Shahrudin, 2021), near areas consistently showed higher SM than far areas, reinforcing the importance of water availability for *Nepenthes* distribution. SOC is a key indicator of soil quality, governing nutrient cycling, microbial activity, and soil structure (Lehmann and Kleber, 2015). SOC values in this study were lower than those reported from dense *Nepenthes* peatland habitats, but were consistently higher in near areas than in far areas.

The highest SOC occurred in the Jaintia Hills, likely due to greater vegetation density and litter input. The observed inverse relationship between SOC and pH aligns with established mechanisms of soil acidification through organic matter mineralisation (Meurer, 2006). Nitrogen is an essential macronutrient that often limits productivity in terrestrial ecosystems (Schimel and Bennett, 2004). SAN levels in Meghalaya exceeded those reported from several Indonesian *Nepenthes* habitats, likely reflecting differences in soil type, altitude, and vegetation cover (Zhang *et al.,* 2016). SAN concentrations were higher in near areas, particularly elevated in the Jaintia Hills, indicating a potential edaphic basis for the abundance of *N. khasiana* in these regions. Phosphorus availability is strongly regulated by soil pH and organic matter dynamics (Sharma and Sharma, 2004). Although phosphorus availability is typically highest near neutral pH, in this study, the soil samples showed relatively high SAP, especially in the Jaintia Hills, where SOC was also elevated. SAP values were considerably higher than those reported from several Indonesian *Nepenthes* habitats (Mansur *et al.,* 2024), highlighting regional

Table 3: Total variance explained for the near pitcher plant area in Garo, Khasi and Jaintia Hills of Meghalaya

Sample areas	Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
		Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
Garo Hills	1	5.340	44.497	44.497	5.340	44.497	44.497	4.882	40.687	40.687
	2	4.030	33.584	78.081	4.030	33.584	78.081	3.425	28.540	69.227
	3	1.814	15.118	93.199	1.814	15.118	93.199	2.877	23.972	93.199
	4	0.816	6.801	100						
	5	2.36E-16	1.97E-15	100						
	6	1.32E-16	1.10E-15	100						
	7	-4.83E-17	-4.03E-16	100						
	8	-8.20E-17	-6.83E-16	100						
	9	-1.36E-16	-1.14E-15	100						
	10	-2.08E-16	-1.74E-15	100						
	11	-4.92E-16	-4.10E-15	100						
	12	-1.60E-15	-1.33E-14	100						
Khasi Hills	1	6.150	51.248	51.248	6.150	51.248	51.248	4.279	35.654	35.654
	2	2.492	20.764	72.011	2.492	20.764	72.011	3.610	30.083	65.737
	3	1.851	15.421	87.433	1.851	15.421	87.433	2.087	17.394	83.131
	4	1.508	12.567	100	1.508	12.567	100	2.024	16.869	100
	5	2.43E-16	2.02E-15	100						
	6	1.39E-16	1.16E-15	100						
	7	2.06E-17	1.72E-16	100						
	8	-2.45E-17	-2.04E-16	100						
	9	-1.21E-16	-1.01E-15	100						
	10	-1.93E-16	-1.60E-15	100						
	11	-2.39E-16	-1.99E-15	100						
	12	-5.05E-16	-4.21E-15	100						
Jaintia Hills	1	6.072	50.596	50.596	6.072	50.596	50.596	5.881	49.009	49.009
	2	2.988	24.900	75.496	2.988	24.900	75.496	2.362	19.686	68.695
	3	1.850	15.418	90.914	1.850	15.418	90.914	1.890	15.750	84.445
	4	1.090	9.086	100	1.090	9.086	100	1.867	15.555	100
	5	6.38E-16	5.31E-15	100						
	6	2.79E-16	2.33E-15	100						
	7	1.18E-16	9.83E-16	100						
	8	6.50E-17	5.42E-16	100						
	9	-1.04E-16	-8.64E-16	100						
	10	-1.29E-16	-1.08E-15	100						
	11	-2.14E-16	-1.78E-15	100						
	12	-3.26E-16	-2.72E-15	100						
Combined Hills	1	5.166	43.047	43.047	5.166	43.047	43.047	4.153	34.610	34.610
	2	2.622	21.846	64.893	2.622	21.846	64.893	2.865	23.877	58.487
	3	1.600	13.332	78.224	1.600	13.332	78.224	1.951	16.262	74.749
	4	1.020	8.496	86.720	1.020	8.496	86.720	1.437	11.971	86.720
	5	0.690	5.748	92.469						
	6	0.446	3.718	96.186						
	7	0.197	1.642	97.829						
	8	0.136	1.135	98.964						
	9	0.076	0.635	99.599						
	10	0.035	0.288	99.887						
	11	0.010	0.086	99.973						
	12	0.003	0.027	100						

differences in soil fertility. Slightly higher mean SAP in far areas may reflect complex interactions involving leaching, organic matter immobilisation, and rainfall intensity (Gerhard *et al.,* 2021). Potassium plays a vital role in plant physiological processes and is closely linked to organic matter decomposition (Six *et al.,* 2002). SAK was consistently higher in pitcher plant areas than in far areas and was found to be highest in the Jaintia Hills. These values exceeded those reported from other *Nepenthes* habitats (Mansur *et al.,* 2024), suggesting that potassium may contribute to habitat suitability for *N. khasiana.* SNI revealed high SOC, SAP

Table 4: Component matrix and rotated component matrix for near pitcher plant areas in Garo, Khasi, and Jaintia hills of Meghalaya

Parameters	Component	Garo		Khasi		Jaintia		Combined	
		CM	RCM	CM	RCM	CM	RCM	CM	RCM
pH	PC1	0.336	-0.045	-0.868	-0.828	-0.217	-0.123	0.322	0.007
	PC2	0.724	0.313	0.345	-0.261	0.489	0.962	-0.459	-0.167
	PC3	-0.589	0.941	0.252	-0.079	-0.845	-0.244	0.766	0.938
	PC4	--	--	0.252	0.490	0.003	0.027	-0.089	0.017
SM	PC1	0.926	0.916	0.380	0.001	0.891	0.962	0.977	0.838
	PC2	-0.109	-0.018	0.066	0.031	0.452	0.184	0.103	-0.406
	PC3	0.129	0.216	-0.142	0.998	0.014	0.183	0.040	0.225
	PC4	--	--	0.912	-0.052	0.040	0.087	0.103	0.242
SOC	PC1	-0.846	-0.957	0.914	0.482	0.935	0.885	0.660	0.905
	PC2	0.392	0.177	0.080	0.478	-0.258	-0.376	0.664	-0.068
	PC3	-0.287	0.075	-0.197	0.665	0.101	-0.246	-0.061	-0.148
	PC4	--	--	0.345	-0.311	0.220	-0.119	-0.152	-0.240
SAN	PC1	-0.721	-0.800	0.847	0.755	0.981	0.968	0.977	0.839
	PC2	0.617	0.511	-0.305	0.167	-0.015	-0.050	0.136	-0.484
	PC3	-0.017	0.020	0.184	0.632	-0.119	-0.210	-0.010	0.174
	PC4	--	--	0.394	0.047	0.150	-0.127	-0.065	0.092
SAP	PC1	0.014	0.066	-0.558	0.018	-0.254	-0.030	0.296	0.061
	PC2	-0.884	-0.969	-0.788	-1.000	0.695	0.293	-0.379	-0.087
	PC3	-0.411	-0.093	-0.082	0.003	0.114	0.041	-0.077	0.125
	PC4	--	--	0.245	0.015	0.663	0.955	0.712	0.847
SAK	PC1	0.808	0.879	0.829	0.951	0.975	0.970	0.765	0.906
	PC2	0.086	0.324	-0.469	0.182	0.180	0.079	0.486	-0.083
	PC3	0.467	-0.003	0.008	-0.015	-0.064	0.085	0.003	-0.005
	PC4	--	--	-0.305	-0.251	-0.115	-0.213	0.108	0.068
Zn	PC1	-0.842	-0.735	-0.459	-0.910	0.932	0.988	0.573	0.853
	PC2	0.229	0.323	0.798	0.329	0.274	-0.028	0.606	0.217
	PC3	0.259	-0.429	-0.390	-0.118	0.101	0.035	0.150	0.030
	PC4	--	--	-0.034	-0.224	0.214	0.150	0.254	0.085
Cu	PC1	0.007	-0.001	-0.481	0.037	0.578	0.626	-0.720	-0.268
	PC2	0.832	0.976	-0.320	-0.456	0.619	0.560	0.391	0.921
	PC3	0.511	-0.001	0.813	-0.203	-0.190	0.486	0.403	0.028
	PC4	--	--	0.063	0.866	-0.496	-0.243	0.309	-0.094
Fe	PC1	0.189	0.461	0.944	0.802	-0.077	-0.009	0.223	-0.023
	PC2	-0.930	-0.654	-0.046	0.562	0.581	-0.009	-0.288	-0.480
	PC3	0.262	-0.573	0.304	0.187	0.645	0.990	-0.778	-0.539
	PC4	--	--	-0.122	0.075	-0.490	0.140	0.275	0.541
Mn	PC1	-0.648	-0.300	0.762	0.156	-0.366	-0.211	-0.877	-0.496
	PC2	-0.245	0.162	0.630	0.909	0.585	-0.122	0.264	0.752
	PC3	0.721	-0.940	0.103	0.387	0.701	0.633	-0.014	-0.331
	PC4	--	--	0.106	0.010	0.178	0.735	0.286	-0.021
Ni	PC1	0.709	0.606	0.885	0.605	0.978	0.926	-0.370	0.213
	PC2	0.570	0.616	0.231	0.790	-0.147	-0.310	0.766	0.809
	PC3	0.236	0.369	0.147	-0.041	0.147	-0.041	0.163	-0.243
	PC4	--	--	-0.375	-0.086	0.019	-0.211	0.220	-0.199
Pb	PC1	0.901	0.706	-0.045	-0.150	-0.278	-0.093	0.491	0.100
	PC2	0.419	0.317	0.486	0.412	0.895	0.862	-0.549	-0.271
	PC3	-0.092	0.630	0.865	0.033	-0.346	0.251	0.429	0.701
	PC4	--	--	0.117	0.898	0.035	0.431	0.299	0.491

CM: Component matrix; RCM: Rotated component matrix; SM: Soil moisture, SOC: Soil organic carbon, SAN: Soil available nitrogen, SAP: Soil available phosphorus, SAK: Soil available potash

and SAK across near sites, but consistently low nitrogen status, which is in agreement with the earlier studies from Meghalaya (Das *et al.,* 2014; Sen *et al.,* 2017). This pattern underscores nitrogen limitation even in relatively organic-rich soils.

Micronutrients and heavy metals, like Zn, Fe, Mn, Cu, Pb and Ni, occur naturally in soil and are influenced by parent material, pH and organic matter (Tangahu *et al.,* 2011). In this study, the Mn concentrations were highest in more acidic Khasi

Table 5: Linear mixed model - Estimates of Fixed Effects

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	3.307444E1	3.694912E1	22	0.895	0.380	-43.553339	109.702228
[parameter=1]	3.213333E0	4.837775E1	22	0.066	0.948	-97.115986	103.542653
[parameter=2]	1.554667E1	4.837775E1	22	0.321	0.751	-84.782653	115.875986
[parameter=3]	0.066667	4.837775E1	22	0.001	0.999	-100.262653	100.395986
[parameter=4]	1.444533E2	4.837775E1	22	2.986	0.007	44.124014	244.782653
[parameter=5]	3.518333E1	4.837775E1	22	0.727	0.475	-65.145986	135.512653
[parameter=6]	2.041633E2	4.837775E1	22	4.220	0.000	103.834014	304.492653
[parameter=7]	0.046667	4.837775E1	22	0.001	0.999	-100.282653	100.375986
[parameter=8]	-0.166667	4.837775E1	22	-0.003	0.997	-100.495986	100.162653
[parameter=9]	7.795333E1	4.837775E1	22	1.611	0.121	-22.375986	178.282653
[parameter=10]	1.996333E1	4.837775E1	22	0.413	0.684	-80.365986	120.292653
[parameter=11]	-1.006667E0	4.837775E1	22	-0.021	0.984	-101.335986	99.322653
[parameter=12]	0	0	-	-	-	-	-
[area=1]	-4.787583E1	2.418888E1	22	-1.979	0.060	-98.040493	2.288826
[area=2]	-4.643750E1	2.418888E1	22	-1.920	0.068	-96.602160	3.727160
[area=3]	0	0	-	-	-	-	-

soils, while Jaintia Hills showed elevated Zn, Fe and Pb, likely reflecting coal-bearing parent materials, mining activity and vehicular emissions (Sanjay-Swami and Lyngdoh, 2019; Mir *et al.,* 2020). Despite elevated levels, all heavy metals remained below international safety thresholds (BIS, EU, and Dutch standards) (Crommentuijn *et al.,* 1997). Consistent with earlier studies (van der Ent *et al.,* 2015), soil supporting pitcher plants exhibited higher micronutrient concentrations than non-inhabited areas. PCA and HCA are effective multivariate tools for identifying key soil variables influencing vegetation patterns (Salami *et al.,* 2016). PCA identified SOC and SAK, Cu and Ni, pH and Pb, and SAP and Fe as key variable groupings, indicating structured edaphic controls across Meghalaya. Dominant drivers varied among hills, with Cu, SM and Fe emerging as key factors in the Garo, Khasi and Jaintia Hills, respectively. Combined PCA results suggest that soil pH, SOC, SAP, SAK, Cu, and Ni substantially influence pitcher plant habitats. HCA grouped most nutrients and metals into pH and organic matter-mediated clusters, while iron showed distinct behaviour due to its unique geochemical properties. Correlation analysis highlighted a strong positive relationship between SOC and SM, SAN, SAK and Zn, emphasising the central role of organic carbon in soil fertility. Linear mixed-effects models further confirmed significant association between SAN, SAK and soil properties influencing *N. khasiana* habitat quality.

Although *Nepenthes* species are typically associated with nutrient-poor environments, this study demonstrates that *N. khasiana* thrives in moderately acidic soils enriched in organic carbon, phosphorus and potassium, despite relatively low nitrogen availability. While carnivory supplements nitrogen and phosphorus (Devi *et al.,* 2019), soil fertility appears to play a crucial role in sustaining populations of carnivorous plants (Stewart and Nilsen, 1993). Despite limitations such as lack of seasonal sampling and limited replication, this study provides valuable insights into the edaphic requirements of *N. khasiana*. Understanding these soil-plant relationship is essential for their conservation planning, habitat restoration, and sustainable management in Meghalaya. These findings reveal that *N. khasiana* prefers acidic yet nutrient-enriched soils and highlight the critical role of soil quality in its conservation. Integrating soil quality considerations into conservation strategies may enhance both *in-situ* resilience and *ex-situ* conservation efforts for this endangered and endemic species.

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References

Adamec, L., I. Matusikova and A. Pavlovic: Recent ecophysiological, biochemical and evolutionary insights into plant carnivory. *Ann. Bot.,* **128**, 241-259 (2021).

Arruda, S.C.C., A.L.D. Silva, R.M. Galazzi, R.A. Azevedo and M.A.Z. Arruda: Nanoparticles applied to plant science: a review. *Talanta,* **131**, 693-705 (2015).

Becknell, J.M. and J.S. Powers: Stand age and soils as drivers of plant functional traits and aboveground biomass in secondary tropical dry forest. *Can. J. For. Res.,* **44**, 604-613 (2014).

Bhattacharya, A., S.G. Momin and P. Sarkar: New distribution records of the endemic pitcher plant, *Nepenthes khasiana* Hook. f. and identification of threats in Meghalaya, India. *J. Environ. Biol.,* **45**, 1–7 (2024).

CITES-UNEP: The CITES Appendices. https://cites.org/eng/app/index.php (2022). Accessed 23 May 2024.

Clarke, C. and J.A. Moran: Climate, soils and vicariance–their roles in shaping the diversity and distribution of *Nepenthes* in Southeast Asia. *Plant Soil,* **403**, 37-51 (2016).

Crommentuijn, T., M.D. Polder and E.J. van de Plassche: Maximum permissible concentrations and negligible concentrations for metals, taking background concentrations into account. RIVM Report 601501001, Bilthoven, Netherlands, 260 pages (1997).

Das, A., D.P. Patel, G.C. Munda, G.I. Ramkrushna, M. Kumar and S.V. Ngachan: Improving productivity, water and energy use efficiency in lowland rice (*Oryza sativa*) through appropriate establishment methods and nutrient management practices in the mid-altitude of north-east India. *Exp. Agric.,* **50**, 353-375 (2014).

Devi, S.P., S. Kumaria, P.R. Sharma, P. Khoyumthem and P. Tandon: *Nepenthes khasiana* Hook f., an endangered tropical pitcher plant of India. *Indian J. Tradit. Knowl.,* **18**, 68-75 (2019).

Dickman, S.R. and H.R. Bray: Colorimetric determination of phosphate. Ind. *Eng. Chem. Anal. Ed.,* **12**, 665-668 (1940).

Dikshit, K.R. and J.K. Dikshit: Weather and climate of North-East India. In: North-East India: Land, People and Economy (Eds.: K.R. Dikshit and J.K. Dikshit). Adv. Asian Hum-Environ. Res., Springer, Dordrecht, pp. 149-173 (2014).

Ding, C., T. Zhang, X. Wang, F. Zhou, Y. Yang and Y. Yin: Effects of soil type and genotype on lead concentration in rootstalk vegetables and the selection of cultivars for food safety. *J. Environ. Manage.,* **122**, 8-14 (2013).

Ellison, A.M. and N.J. Gotelli: Nitrogen availability alters the expression of carnivory in the northern pitcher plant, *Sarracenia purpurea*. *Proc. Natl. Acad. Sci. USA,* **99**, 4409-4412 (2002).

Finck, A.: Pflanzenernährung in Stichworten. Verlag Ferdinand Hurt, Kiel, 200 pages (1976).

Gerhard, L., H. Puhlmann, M. Vogt and J. Luster: Phosphorus leaching from naturally structured forest soils is more affected by soil properties than by drying and rewetting. *Front. For. Glob. Change,* **4**, 543037 (2021).

Haliru, H.A., L.P. Ling and O.S. Selaman: Environmental burden of heavy metal contamination levels in soil from sewage irrigation area of Geriyo catchment, Nigeria. *Civil Environ. Res.,* **6**, 118-125 (2014).

Hanway, J.J. and H. Heidal: Soil analysis, as used in Iowa State College of Soil Testing Laboratory. *Iowa Agric.,* **57**, 1-31 (1952).

Hidayat, S., H. Helmanto, Dodo, D.W. Purnomo and I. Supriyatna: Habitat of *Nepenthes* spp. in the area of Sampit Botanic Gardens, Central Kalimantan, Indonesia. *Biodiversitas,* **19**, 1258-1265 (2018).

Jackson, M.L.: Soil Chemical Analysis. Prentice Hall of India, New Delhi, 498 pages (1967).

Kamble, M.V., S. Harikrishnan and P. Balakumar: *Utricularia caerulea* (Lentibulariaceae): a new record to flora of Andaman and Nicobar Islands. *Rheedea,* **22**, 116-118 (2012).

Kekane, S.S., R.P. Chavan, D.N. Shinde, C.L. Patil and S.S. Sagar: A review on physico-chemical properties of soil. *Int. J. Chem. Stud.,* **3**, 29-32 (2015).

Lehmann, J. and M. Kleber: The contentious nature of soil organic matter. *Nature,* **528**, 60-68 (2015).

Lindsay, W.L. and W.A. Norvell: Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.,* **42**, 421-428 (1978).

Mangosongo, H.M., H.V. Lyaruu and E.E. Mneney: Agro-morphological characterization of the wild rice (*Oryza longistaminata*) populations from selected areas of Tanzania. *Tanzan. J. Sci.,* **45**, 9-17 (2019).

Mansur, M., A. Salamah, E. Mirmanto and F.Q. Brearley: Ecology of Nepenthes on Mount Talang, West Sumatra, Indonesia. *Trop. Ecol.,* **65**, 460-469 (2024).

Mao, A.A. and P. Kharbuli: Distribution and status of *Nepenthes khasiana* Hook. f., a rare endemic pitcher plant of Meghalaya, India. *Phytotaxonomy,* **2**, 77-83 (2002).

Meurer, E.J.: Soil Chemistry Fundamentals. Evangraf, Porto Alegre, Brazil, 190 pages (2006).

Minasny, B., S.Y. Hong, A.E. Hartemink, Y.H. Kim and S.S. Kang: Soil pH increase under paddy in South Korea between 2000 and 2012. *Agr. Ecosyst. Environ.,* **221**, 205-213 (2016).

Mir, S.A., J.I.A. Bhat, F. Lone, M.U. Rehman, T. Ali, N. Nazir and A.A. Lone: Impact of vehicular pollution on nutrient status of roadside soils. *Int. J. Chem. Stud.,* **8**, 191-195 (2020).

Nair, P.K.R., R.J. Buresh, D.N. Mugendi and C.R. Latt: Nutrient cycling in tropical agroforestry systems: myths and science. In: Agroforestry in Sustainable Agricultural Systems (Eds.: L.E. Buck, J.P. Lassoie and E.C.M. Fernandes). Lewis Publishers, USA, pp. 1-31 (1999).

Parker, F.W., W.L. Nelson, E. Winters and J.E. Miles: The broad interpretation and application of soil test summaries. *Agron. J.,* **43**, 103-112 (1951).

Parmar, J.K.: Study of presence of available potassium and fertility index of farmland soil of Danta Taluka Territory District: Banaskantha (Gujarat). *Int. J. Sci. Res.,* **5**, 604-608 (2016).

Piper, C.S.: Soil and plant analysis. Hans Publisher, Bombay, 368 pages (1966).

Rahim, S.A., T. Lihan, Z.A. Rahman, W.M.R. Idris, A. Hashim, S.M. Yusof and L.H. Yin: Uptake of Fe, Mn and Cu by *Nepenthes* sp. in ex-mining soil at Pelepah Kanan Kota Tinggi, Johor. *Sains Malays.,* **36**, 123-132 (2007).

Ramamoorthy, B. and J.C. Bajaj: Available N, P and K status of Indian soils. *Fertil. News,* **14**, 24-26 (1969).

Rawi, N.H.Z. and R. Shahrudin: Species richness and soil properties in Nepenthes habitat at bris ecosystem in Setiu, Terengganu. *UMT J. Undergrad. Res.,* **3**, 67-72 (2021).

Saha, R., R.S. Chaudhary and J. Somasundaram: Soil health management under hill agroecosystem of North East India. *Appl. Environ. Soil Sci.,* **2012**, Article ID 696174 (2012).

Salami, B.T., J.A. Okogun and N. Sanginga: Delineation of management zones by classification of soil physico-chemical properties in the Northern Savanna of Nigeria. *Front. Agric. Food Technol.,* **6**, 1-8 (2016).

Sanjay-Swami and E.A.S. Lyngdoh: Restoration of degraded land in coal mine areas of Jaintia Hills, Meghalaya through phytoremediation. *Soil Water Conserv. Bull.,* **4**, 17-24 (2019).

Santapau, H. and A.N. Henry: A dictionary of the flowering plants in India. Publication and Information Directorate, New Delhi, 198 pages (1976).

Schimel, J.P. and J. Bennett: Nitrogen mineralization: challenges of a changing paradigm. *Ecology,* **85**, 591-602 (2004).
Sen, A., J. Mukhim, A. Debnath and P. Barman: Distribution of sulphur in some soils of Meghalaya. *J. Exp. Agric. Int.,* **16**, 1-9 (2017).
Setiawan, H., L. Hakim, A.A.R. Fernandes, Antonius and C. Retnaningdyah: The ecology of *Nepenthes* in Sintang Regency, West Kalimantan, Indonesia. *Environ. Ecol. Res.,* **13**, 47-59 (2025).
Sharma, J.C. and Y. Sharma: Effect of forest ecosystems on soil properties—A review. *Agric. Rev.,* **25**, 16-28 (2004).
Sim, J.W.S., H.T.W. Tan and I.M. Turner: Adinandrabelukar: an anthropogenic heath forest in Singapore. *Vegetatio,* **102**, 125-137 (1992).
Six, J., R.T. Conant, E.A. Paul and K. Paustian: Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil,* **241**, 155-176 (2002).
Stewart, C.N. and E.T. Nilsen: Responses of *Drosera capensis* and *D. binata var. multifida* (Droseraceae) to manipulations of insect availability and soil nutrient levels. *New Zealand J. Bot.,* **31**, 385-390 (1993).
Subbiah, B.V. and G.L. Asija: A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.,* **25**, 259-260 (1956).
Tangahu, B.V., S.R.S. Abdullah, H. Basri, M. Idris, N. Anuar and M. Mukhlisin: A review on heavy metals As, Pb and Hg uptake by plants through phytoremediation. *Int. J. Chem. Eng.,* Article ID 939161 (2011).
Topp, G.C.: Soil water content. In: Soil sampling and methods of analysis (Ed.: M.R. Carter). Lewis Publishers, Boca Raton, pp. 541-558 (1993).
van der Ent, A., S. Sumail and C. Clarke: Habitat differentiation of obligate ultramafic *Nepenthes* endemic to Mount Kinabalu and Mount Tambuyukon (Sabah, Malaysia). *Plant Ecol.,* **216**, 789-807 (2015).
Ved, D., D. Saha, K. Haridasan and K. Ravikumar: *Nepenthes khasiana*. The IUCN Red List of Threatened Species 2015:e. T48992883A49009685 (2015). https://doi.org/10.2305/IUCN. UK. 2015-2. RLTS. T48992883A49009685.en
Verma, P.K., J. Schlauer, K.K. Rawat and K. Giri: Status of insectivorous plants in northeast India. *Carniv. Pl. Newslett.,* **43**, 49-58 (2014).
Walkley, A. and I. Black: An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.,* **37**, 29-38 (1934).
Xiao, C., R. You, N. Zhu, X. Mi, L. Gao, X. Zhou and G. Zhou: Variation of soil physicochemical properties of different vegetation restoration types on subtropical karst area in Southern China. *PLoS One,* **18**, e0282620 (2023).
Zhang, Q., Y. Li and X. Yang: Soil pH and nutrient availability regulate soil microbial communities in a long-term fertilization experiment. *Soil Biol. Biochem.,* **98**, 37-49 (2016).
Ziemer, B.: Exciting conservation news: The rare *Nepenthes* collection project. *Carniv. Pl. Newslett.,* **39**, 67 (2010).