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Ecological Determinants of *Nepenthes khasiana* Distribution: A Study of Slope Orientation and Altitude in Meghalaya, India

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ABSTRACT

Pitcher plant, *Nepenthes khasiana* Hook. f. (Nepenthaceae), is a carnivorous plant distributed in the hilly terrain in Meghalaya, India. Although scattered information is available on their distribution, none of the studies covered the role of slope orientation on the distribution of pitcher plants. Therefore, the trail survey method was employed during the survey between 2018 and 2025 to determine the distribution of pitcher plants with respect to elevation and slope orientation. Wherever there was a sighting of a pitcher plant, the GPS coordinate as well as landscape parameters were recorded. The study clearly demonstrates that *N. khasiana* exhibits a unique altitudinal distribution, predominantly limited to mid-elevation montane regions that range from approximately 500 to 1,500 m above sea level. This species shows a strong preference for open areas and sloped landscapes. Moreover, the dominance of northwest-facing slopes emphasizes the importance of slope orientation (255–360°). These findings underscore that elevation, slope selection, and slope orientation together influence the spatial distribution and ecological niche of *N. khasiana* across its distribution range in the hilly areas of Meghalaya, India. The present study could be used by the policymakers and stakeholders for identifying priority conservation habitats, regulating land-use change and mining activities in sensitive areas, developing habitat restoration programmes on suitable

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slopes, strengthening in-situ conservation and long-term population monitoring, and formulating site-specific management strategies to save this endemic carnivorous plant from extinction.

Keywords: Pitcher Plant; *Nepenthes khasiana*; Elevation; Slope Orientation; Distribution

1. Introduction

Nepenthes khasiana Hook. f. (**Figure 1**), a pitcher plant endemic to northeast India^[1,2], belongs to the “Indo-Burma” biodiversity hotspot of the world. In India, they inhabit tropical and subtropical climatic regions at the Garo,

Khasi, and Jaintia Hills of Meghalaya^[3–7] and are also reported from the Dima Hasao area of Assam^[8]. It is categorized as an endangered species in the Red Data Book by SSC-IUCN^[9], as an Appendix-I category by CITES, and under the Negative List of Export by the Government of India^[10].



Figure 1. Pitcher plant, *Nepenthes khasiana* Hook. f., endemic to Northeast India.

Pitcher plants are unique and specialized carnivorous plants that play a significant role in their ecosystems^[11–14]. They play a significant ecological role in the nutrient-poor, acidic soils of Meghalaya by supplementing nitrogen and phosphorus through carnivory, thereby enhancing survival in oligotrophic habitats^[15–17]. By trapping insects, it contributes to local nutrient cycling and helps regulate arthropod populations. The pitchers also function as microhabitats for specialized invertebrates, forming unique pitcher-associated food webs^[18–20]. As an endemic and threatened species, *Nepenthes species* serve as an important indicator of habitat quality and ecological integrity in the hill ecosystems^[21,22]. Its conservation is therefore critical for maintaining regional biodiversity and ecosystem functioning^[23].

Studies are also there on the ethnological use of pitcher plants in treating various diseases that cause loss of their population size in the wild. The fluids of unopened pitchers of *N. khasiana* have been traditionally used to treat various

eye-related ailments^[24]. The plant has also been utilized in the treatment of skin diseases^[25,26], as well as for stomach disorders, diabetes, ear problems, and gynecological conditions^[27]. Experimental studies further demonstrated the potential hypoglycemic and hypolipidemic effects of leaf extracts of *N. khasiana* in dexamethasone-induced hyperlipidemia and insulin resistance in rats, showing significant glucose and lipid-lowering activity and thereby supporting its traditional use in the treatment of diabetes^[28]. The liquid from the pitchers is traditionally consumed by Khasi communities as a morning digestive tonic^[29], while powdered pitcher material of *N. khasiana* is used to treat cholera. However, the rising ethnomedicinal demand has resulted in overharvesting, which is increasingly threatening natural populations^[30].

Scattered information is also available about the habitat pattern of *N. khasiana*, which commonly grows terrestrially on sandy, acidic soils at the margins of the forests, among

recovering secondary vegetation, on bare substrate and scrub, landslide areas, and roadside embankments, usually in strong or direct sunlight^[31]. On the other hand, various disturbance agents such as coal mining, limestone extraction, overexploitation, jhum cultivation, forest fires, etc. affect the natural growth of *N. khasiana* in the Nokrek Biosphere Reserve of Meghalaya, India^[32,33]. They also reported that the inevitable pressure due to commercialization of *N. khasiana* is leading to severe destruction of the species and may create the scarcity of that species in the near future. Therefore, suggestions were given for an immediate conservation and sustainable use of *N. khasiana* for the local people by government and non-government agencies. In 2003, the CAMP meeting held in Guwahati, Assam, stated a total 40% loss of *N. khasiana* population in Meghalaya or its distribution range^[9]. Hence, conservation of this species needs protection of the species and their habitats. Some conservation initiatives had already been taken by the Meghalaya Forest Department by declaring the Baghmara Pitcher Plant Sanctuary in South Garo Hills in Meghalaya for safeguarding the species in the wild^[34]. In addition to this, gene preservation and vegetative propagation techniques are also applied for ex situ conservation^[35–38]. One such endeavor is located in Shillong, Meghalaya, at the National Orchidarium and Experimental Garden of the Botanical Survey of India^[39]. The North Eastern Hill University in Shillong and other government agencies have implemented a number of in situ and ex situ (off-site) conservation initiatives. To maintain *N. khasiana*, methods including tissue culture, micropropagation, and germplasm preservation have been used. The Meghalaya Forest Department is restoring the plants in the East Khasi Hills by means of tissue culture. The inhabitants are now introducing and caring for plants in nature^[40]. Besides, an apex court imposed an Eco-sensitive Zone of 10 km surrounding the pitcher plant sanctuary in December 2018. In spite of all these efforts, pitcher plant populations are declining continuously in their habitats due to human-induced developmental factors.

Several occasional studies confirmed the presence of *N. khasiana* from only the Meghalaya state of India^[1] in different localities, namely Jarain, Sutnga, Jowai, Magheshkola, and Lawbah^[41]. A recent systematic survey established their detailed distribution within their distribution range in the Meghalaya state, covering the Jaintia, Garo, and Khasi Hills

of India^[6,7]. Very recently, the presence of *N. khasiana* has also been discovered in the Dima Hasao area of Assam, India^[8]. This confirms that the species is highly endemic and confined to Meghalaya and its neighbouring area in Assam. Topography plays an important role in influencing the abundance, distribution, and diversity of vegetation^[42–44]. In mountain areas, landscape parameters like elevation, slope aspect, slope position, and slope orientation also affect the vegetation diversity and distribution patterns^[45,46]. All these studies covered only the distribution and altitudinal gradients; however, none of these studies covered the role of slope and slope orientation on the distribution of *N. khasiana* within its distribution range. Hence, this study aimed to find out some landscape parameters like elevation and slope orientation that ultimately act as suitable habitats for this insectivorous plant.

2. Study Area

The study was conducted in some selected locations covering all three hills (Garo, Khasi, and Jaintia) in the Meghalaya state of India, located between 24°58' N and 26°07' N latitude and 89°48' E and 92°51' E longitude (**Figure 2**). Goalpara, Kamrup, and Nagaon districts in Assam form the state's northern border. Karbi Anglong and North Cachar Hills districts in Assam form the state's eastern border. Bangladesh forms the state's southern and western borders. The total area enclosed by the state is 22,429 km². The elevation of the plateau stretches from 150 m to 1,961 m.

The climate in Meghalaya is humid but changes with the monsoon. The western part of the state receives an average yearly rainfall of around 2,600 mm, while annual rainfall is between 2,500 and 3,000 mm in northern Meghalaya. Southeastern Meghalaya gains annual showers of above 4,000 mm.

Meghalaya is a forested terrain with one-third of the state covered by forests. The total estimated forest area in the state is 8,510 km². 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.

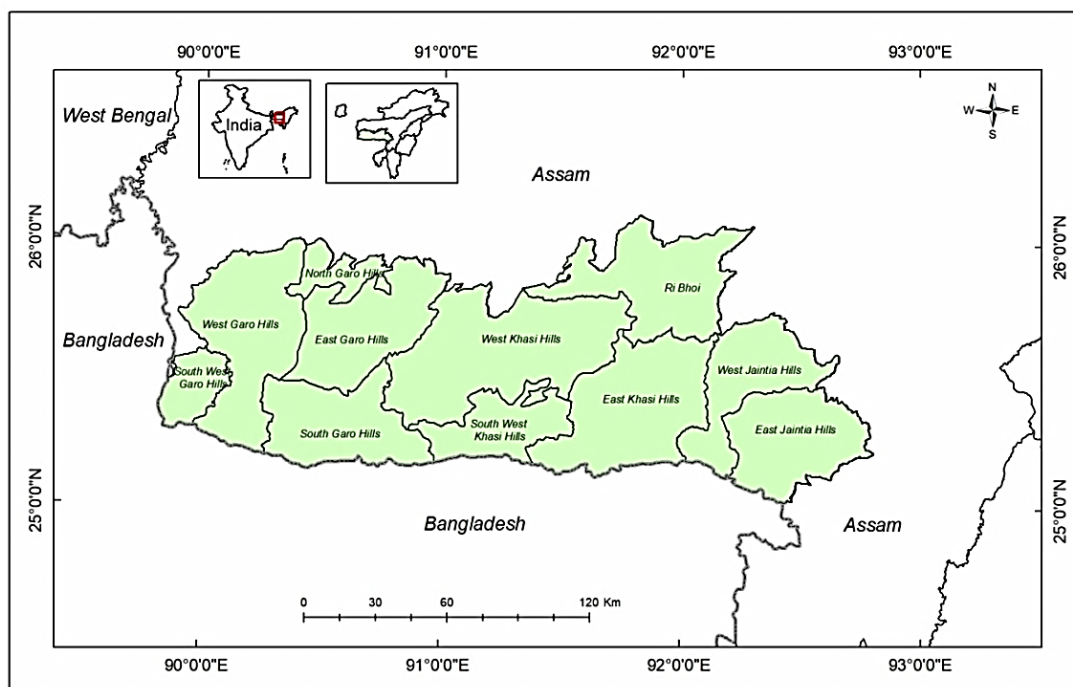


Figure 2. Map of Meghalaya, India, showing the different hills where this study was conducted.

3. Materials and Methods

Due to the isolated distribution of the pitcher plant, a reconnaissance survey was conducted utilizing available literature, a questionnaire survey, and field visits across all three hills (Garo, Khasi, and Jaintia) in Meghalaya from 2018 to 2025, leading to the identification of potential distribution areas. In each of these identified locations, the trail survey method^[47–49] was employed. In areas where the pitcher plant was located, the GPS coordinates and elevations of the site were documented using a Garmin Etrex 10 device. All the coordinates were plotted in the outline map for preparing the distribution map. For preparing the elevation map, the SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) data of 30 m resolution were used. At the initial stage, the DEM data were reprojected into UTM (Universal Transverse Mercator) zone 46 N and clipped with the state boundary. Further, the elevation ranges were classified into different class intervals. After collecting the GPS coordinates, landscape parameters like elevation and slope were projected on the map. Further, a compass was used to ascertain the suitable hill slope orientation in the distribution of pitcher plants in the form of degrees (360° map)^[50].

4. Results

4.1. Distribution

The survey confirmed the existence of pitcher plants in new areas, specifically Balsri Gittim, Bhawanipur, and Dilsa Jarek/Abri, while also reaffirming their presence in the Bandarigre Community Reserve, Baghmara Pitcher Plant Sanctuary, Karwani Stream, Matcha Nokpante Community Reserve, and Nokrek Biosphere Reserve located in the Garo Hills (**Figure 3** and **Table 1**). These plants were predominantly located on either the slopes of hills or on cliff faces.

In the Khasi Hills, which include the East, West, and South Khasi Hill districts, pitcher plants were discovered in the vicinity of Nonglang, Phlangdilion, Ranikor, Lawbah, Mawsynram, and Pynursla regions (**Figure 3** and **Table 1**).

The pitcher plants have been observed in various new sites within the Jaintia Hills (East and West Jaintia Hill Districts), specifically in and around Ksietphare, Tuber Kmaishnong, Moonpun Falls, Stone Bridge, Tuber Sohshrich, Rymbai, Bataw, Umtasai, Ladwah Wapung, Dain Satlang, Pynurkba, Umsang, Ipmla, Suchen Shnong,

Suchen Mulieh, Lechka Dam site, Suchen Dhana, Deinsalalu, Mukkjai, Shken Pyrsit, Thluamvi, Skhentalang, Thangbuli Road, Amsarim, and Mustem. Their presence has also been reconfirmed in the Jarain area (Figure 3 and Table

1). Nevertheless, the pitcher plants have been eradicated from numerous locations, including Sona Pahar in Khasi Hills and the vicinity of Ampati in South-West Garo Hills, where they were previously documented.

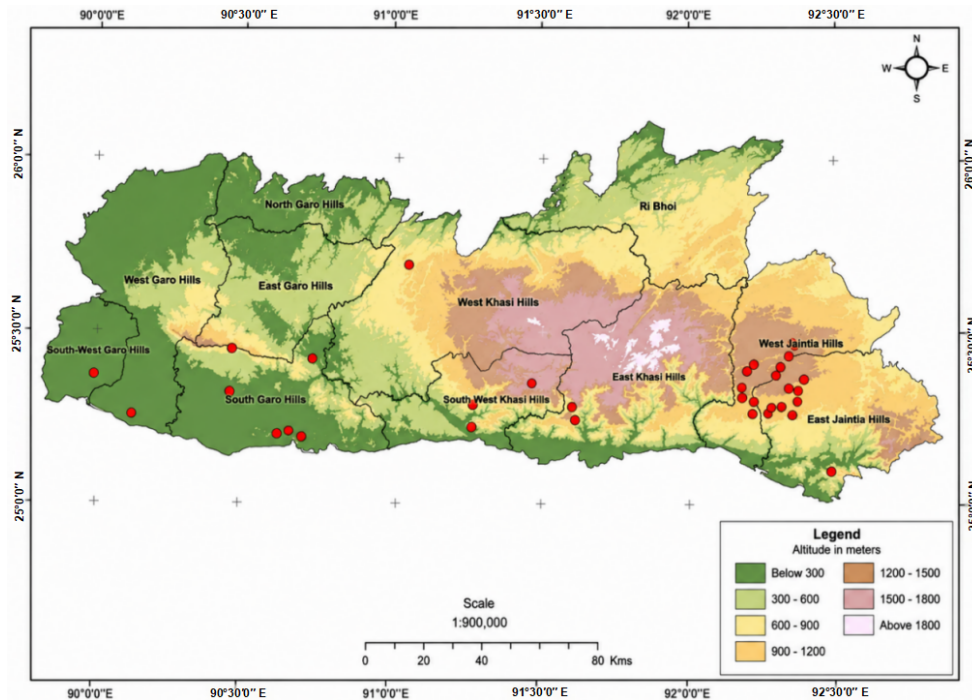


Figure 3. Altitudinal variation in the distribution of the pitcher plant, *N. khasiana*, in Meghalaya, India.

Table 1. Landscape parameters and altitudinal variation in the distribution of pitcher plant, *N. khasiana*, in Meghalaya.

Hills	Distribution	Elevation	Locations	Slope Orientation	Canopy
Jaintia Hills	Ksietphare	1,330	Hill slope	NW	Open
	Tuber Sohshrich	1,400	Hill slope	N	Open
	Moonpun Falls	1,300	Hill slope near river bed	NW	Open
	Stone bridge	1,310	Hill slope	NW	Open
	Tuber Kmaishnong	1,390	Hill slope near river bed	W	Open
	Rymbai	1,200	Hill slope	NE	Open
	Bataw	1,080	Hill slope	NW	Open
	Umtasai	960	Hill slope	N	Open
	Ladwah Wapung	970	Hill slope	W	Open
	Dain Satlang	970	Hill slope	NW	Open
	Pynurkba	930	Hill slope	NW	Open
	Umsang	1,150	Hill slope	N	Open
	Ipmala	1,090	Hill slope	NW	Open
	Suchen Shnong	1,070	Hill slope	W	Open
	Suchen mulieh	960	Hill slope	E	Open
	Lechka Dam site	930	Hill slope	NW	Open
	Suchen Dhana	940	Hill slope	N	Open
	Deinsalalu	1,180	Hill slope	W	Open
	Mukkjai	680	Hill slope	NW	Open
	Jarain	650	Roadside slope	SE	Open
	Shken Pyrsit	680	Plain	N	Open
	Thluamvi	690	Hill cliff	W	Open
	Skhentalang	720	Roadside slope	NW	Open
	Jarain Pitcher Plant Lake	680	Plain	W	Open
	Thangbuli Road	670	Roadside slope	NW	Open
	Amsarim	660	Hill slope	NW	Open
	Mustem	680	Hill cliff	N	Open

Table 1. Cont.

Hills	Distribution	Elevation	Locations	Slope Orientation	Canopy
Garo Hills	Balsri Gittim	610	Roadside slope	NW	Open
	Baghmara Pitcher Plant Sanctuary and Baghmara	630	Hill slope	NW	Open
	Bhawanipur	590	Hill slope	N	Open
	Dilsa Jarek/Abri	690	Hill slope	W	Open
	Matcha-Nokpante Community Conserve Pitcher Plant Reserve	565	Hill slope	NW	Open
	Bandarigre Community Reserve	640	Hill slope	S	Open
	Nokrek Biosphere	1,430	Hill slope	NW	Open
Khasi Hills	Mawsynram	1,200	Hill slope	N	Open
	Nonglang	1,080	Hill slope	SE	Open
	Phlangdilion	940	Hill slope near river bed	W	Open
	Ranikor	830	Hill slope near river bed	N	Open
	Lawbah	800	Hill slope	NW	Open
	Pynursla	1,050	Hill slope	S	Open
	Sona Pahar	870	Hill slope	NW	Open

4.2. Status of the Habitat

Pitcher plants are growing in hilly areas and are mostly found on the hill slope and cliff (Table 1). Occasionally, they were found at the roadside slope and steep riverbed. These slopes varied from moderate to very steep. They occur in both primary and secondary forests. But most of them were found in open-canopy forest habitats with sunlight intensity or partially shaded areas. Except for some protected areas (national parks and wildlife sanctuaries) and non-protected areas (reserved forests) belonging to the forest department, the majority of the pitcher plant distribution sites are located on private land owned by the individual, clan, community, or both. In very few cases, they were also found close to agricultural plots.

4.3. Elevation

In the Jaintia Hills, pitcher plants were documented across a wide elevational range, spanning from approximately 650 m to 1,400 m above mean sea level. The highest elevations were recorded at Tuber Sohshrich (1,400 m), Tuber Kmaishnong (1,390 m), and Ksietphare (1,330 m), demonstrating the presence of pitcher plants in the upper hill slopes. A significant number of sites were found in the mid-elevation range (900–1,200 m), including Rymbai, Umsang, Ipmala, Deinsalalu, and Ladwah Wapung. Lower elevation occurrences (650–720 m) were identified at sites such as Jarain, Mukkjai, Amsarim, Mustem, and Thluamvi (Table 1). Overall, the Jaintia Hills exhibit the broadest elevational distribution, indicating a high level of ecological adaptability

of pitcher plants in this area.

In the Garo Hills, the distribution of pitcher plants was noted between elevations of 565 m and 1,430 m. The highest elevation recorded among all surveyed regions was from the Nokrek Biosphere Reserve (1,430 m), underscoring the significance of protected highland habitats for the conservation of pitcher plants. Most other sites, including Baghmara, Balsri Gittim, Bhawanipur, Bandarigre Community Reserve, and Matcha-Nokpante Community Conserve Pitcher Plant Reserve, were located within a lower to mid-elevation range (565–690 m) (Table 1). This trend suggests that, in the Garo Hills, pitcher plants are primarily associated with lower hill slopes, with fewer but notable occurrences at higher elevations.

In the Khasi Hills, pitcher plants have been documented across an elevation range of approximately 800 m to 1,200 m. The lowest elevation recorded among all study sites was at Lawbah (800 m), with Ranikor (830 m), Sona Pahar (870 m), and Phlangdilion (940 m) exhibiting a consistent distribution, indicating the capacity of pitcher plants to thrive in low elevations. Mid-elevation locations were Nonglang (1,080 m) and Pynursla (1,050 m), while the highest elevation was at Mawsynram (1,200 m) (Table 1). In comparison to the Jaintia and Garo Hills, the Khasi Hills demonstrate a moderate elevational distribution, with a significant concentration at low to mid elevations. This signifies that *N. khasiana* is distributed all over Meghalaya, covering the Garo, Khasi, and Jaintia Hills, on a broad elevational gradient from 500 to 1,500 m above mean sea level. This extensive elevational range underscores the ecological adaptability of the species

and its capacity to inhabit various hillslope environments under open canopy conditions.

There was a significant difference in elevation ($t = 19.794$, $df = 27$, $p = 0.000$) among various areas of the Jaintia Hills of Meghalaya. The t -test depicted a significant difference between different locations in the Khasi Hills of Meghalaya as well as elevation ($t = 6.269$, $df = 6$, $p = 0.001$). Further, various study areas of Garo Hills also dif-

fer significantly by t -test elevation ($t = 19.573$, $df = 5$, $p = 0.000$). There was also a significant difference in elevation between different locations of the Garo, Khasi, and Jaintia Hills of Meghalaya (elevation, $F = 7.147$, $p = 0.022$). The present study illustrated a significant negative correlation in elevation between various locations of the Khasi and Jaintia Hills elevations ($r = -0.819$, $p \leq 0.05$) of Meghalaya (**Table 2**).

Table 2. Correlation analysis of different elevations among various locations in the Garo, Khasi, and Jaintia Hills of Meghalaya.

Locations	Garo Hills	Khasi Hills	Jaintia Hills
Garo Hills	1		
Khasi Hills	-0.225	1	
Jaintia Hills	0.504	-0.819*	1

Note: * $p \leq 0.05$.

The PCA revealed more factor loading in elevation for the Jaintia Hills of Meghalaya, depicting that most of the pitcher plants are located here in the present study (**Figure 4**).

The cluster analysis showed that the elevations of vari-

ous locations of the Garo and Khasi Hills are more closely associated than those of the Jaintia Hills, depicting similarity in elevation in the Garo and Khasi Hills of Meghalaya (**Figure 5**).

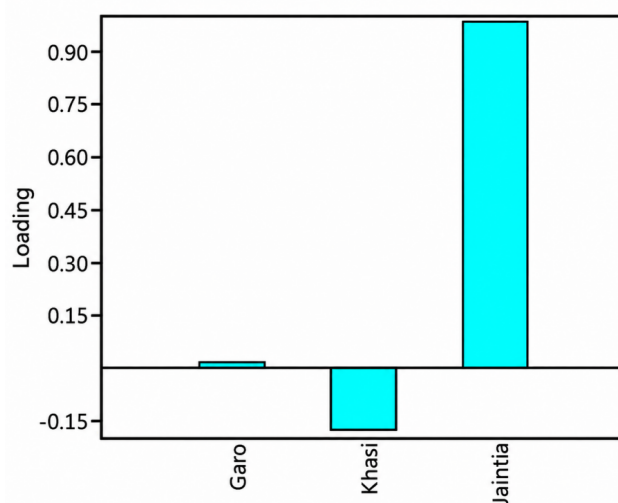


Figure 4. Factor loading of various elevations in the Garo, Khasi, and Jaintia Hills of Meghalaya.

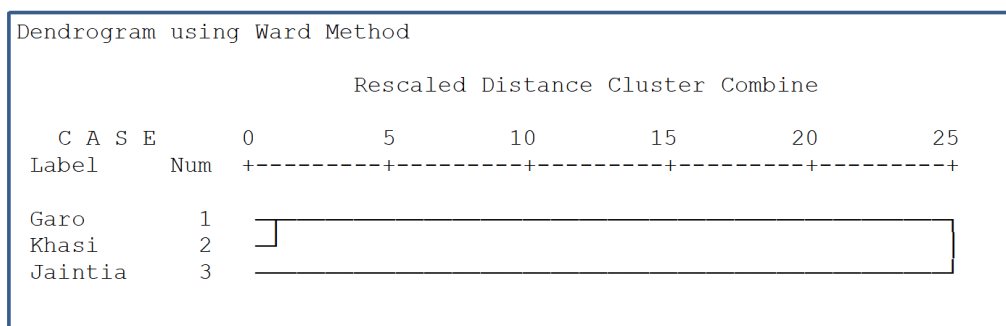


Figure 5. Cluster analysis among various elevations of the Garo, Khasi, and Jaintia Hills in Meghalaya.

4.4. Slope Orientation

The survey found that the sites where pitcher plants are distributed face north to west, with the majority in the north-west orientation, as compared to other slopes. About 70% of the sites are facing between 255 and 3,600, while another 15% of sites have a south-east orientation (Figure 6).

This indicates that slope orientation has some role in the distribution and abundance of pitcher plants in Meghalaya. The *t*-test didn't reveal a significant difference among various locations in slope orientation in the Jaintia and Garo Hills of Meghalaya, whereas in the Khasi Hills, the difference was significant ($t = 3.240$, $df = 6$, $p = 0.018$).

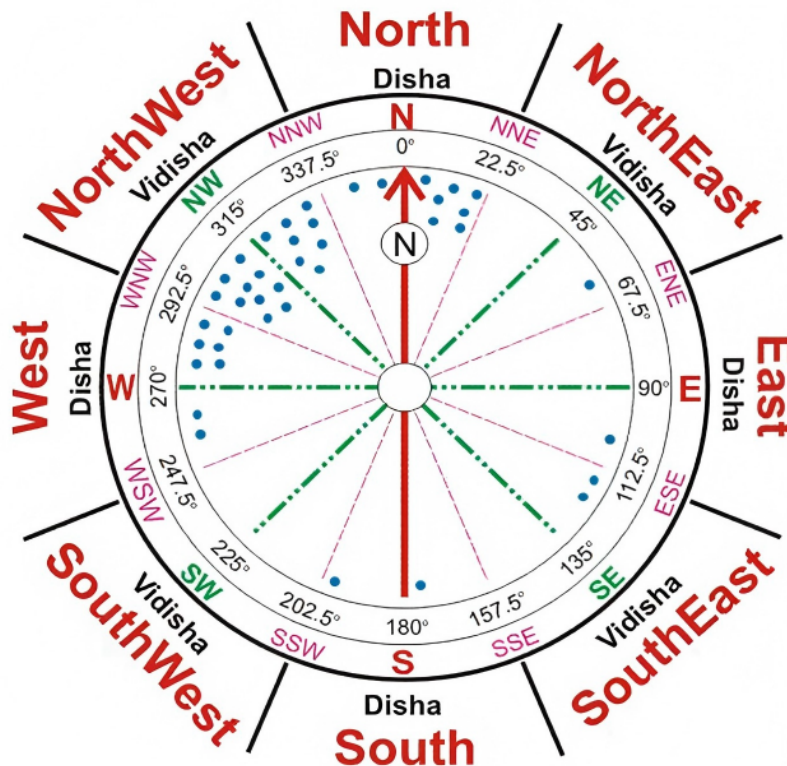


Figure 6. Impact of slope orientation on the distribution of pitcher plants in Meghalaya, India.

The PCA showed that most of the pitcher plants are located in a northwest (NW) orientation on average in all the studied areas of Meghalaya (Figure 7).

The cluster analysis depicted a similarity in orientation for the studied areas where pitcher plants were located in the Garo and Khasi Hills of Meghalaya (Figure 8).

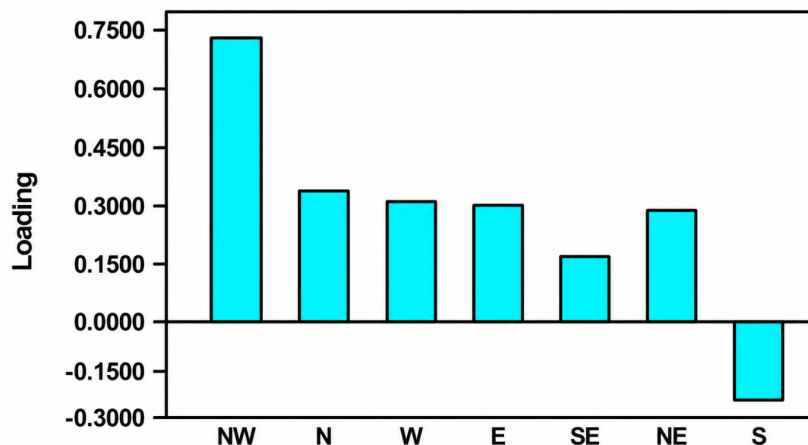


Figure 7. Factor loading of various slope orientations in the Garo, Khasi, and Jaintia Hills of Meghalaya.

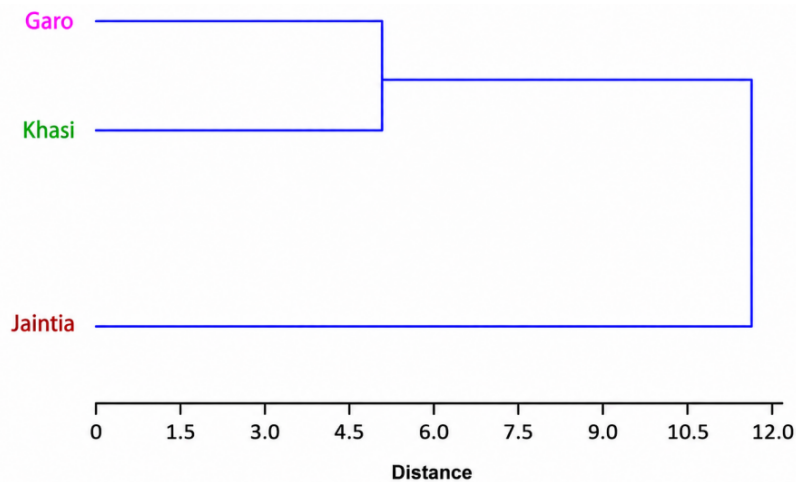


Figure 8. Cluster analysis among various slope orientations of the Garo, Khasi, and Jaintia Hills in Meghalaya.

The correlation analysis revealed a significant positive correlation among the areas facing west and east, west and northeast, and northeast; east and northeast ($r = 1.000$, $p \leq 0.05$), whereas the relationship was negative between west and south, east and south, and northeast and south ($r = -1.000$, $p \leq 0.05$) (**Table 3**).

Table 3. Correlation analysis among various slope orientations in the Garo, Khasi, and Jaintia Hills of Meghalaya.

Slope Orientation	NW	N	W	E	SE	NE	S
NW	1						
N	0.929	1					
W	0.982	0.982	1				
E	0.982	0.982	1.000**	1			
SE	0.327	0.655	0.500	0.500	1		
NE	0.982	0.982	1.000**	1.000**	0.500	1	
S	-0.982	-0.982	-1.000**	-1.000**	-0.500	-1.000**	1

Note: ** $p \leq 0.01$. N: North, S: South, E: East and W: West.

5. Discussion

The present study depicted that the pitcher plant *N. khasiana* is found in reserved forests and community reserve forests, on the roadside cliff and hill slopes near the riverbed. Very occasionally, they were also found near rice fields in private lands. All these locations lie at 650–1,400 m in Jaintia Hills, 565–1,430 m in Garo Hills, and 800–1,200 m in Khasi Hills above mean sea level. This indicates that *N. khasiana* is restricted to between 500 and 1,500 m altitude within its distribution range. Previous studies have reported that *N. khasiana* occurs at altitudes ranging from 1,000 to 1,500 m^[6,7]. Similar patterns were also observed in other *Nepenthes* species, including seven new species that were reported from the central mountains of Mindanao, Philippines, in lower montane forests at around 1,000–1,500 m elevation^[51–53].

In Peninsular Malaysia, two new species of *Nepenthes*

were identified from Terengganu between 850 and 1,100 m elevations in hilly terrain^[54]. Furthermore, six *Nepenthes* species (*N. burbidgeae*, *N. edwardsiana*, *N. rajah*, *N. stenophylla*, *N. tentaculate*, and *N. zakriana*) were reported from elevations ranging between 1,400 and 1,800 m above sea level in the Marai Parai area of Malaysia^[55]. A similar trend was also reported in the case of 31 Bornean *Nepenthes*, which are known to occur at an elevation reaching up to 3,400 m above sea level^[56]. Likewise, the presence of seven species of *Nepenthes* along with two natural hybrids was documented in lowland habitats of Bangka Belitung Island in Indonesia up to 1,000 m in elevation^[57]. The distribution of *Nepenthes lavicola* in Sumatra also inhabits particular elevational ranges from 2,000 to 2,600 m above sea level, underscoring the significance of elevational gradients in assessing habitat suitability for pitcher plants within montane ecosystems^[58]. Hence, our findings on the distribution of *N. khasiana* distinctly reveal a pronounced elevation-dependent pattern, as the species

is predominantly restricted to mid-elevation montane environments (around 500–1,500 m above sea level), aligning with global trends noted in other *Nepenthes* species.

The majority of the *Nepenthes* plants grow well in open or exposed habitats among the shrubs and very rarely occur within lowland dipterocarp and other forests. It was also reported that *Nepenthes* plants are only found in open places and never in shady, primitive forests^[59]. Some species are highly adaptive and can tolerate exposed conditions on mountain ridges. A similar situation has been observed for *Nepenthes* in Singapore^[60]. It was reported that Sumatran *Nepenthes* in both lowland and montane areas grow in exposed habitats such as secondary scrub or bush, roadside clearings, and montane mossy forests^[61]. Open canopy conditions, along with moist or waterlogged and relatively fertile soils, have also been identified as suitable habitats for *Nepenthes* in Sampit Botanic Gardens, Central Kalimantan, Indonesia^[62]. Some studies further indicated that numerous species of *Nepenthes* typically grow in clusters in periodically waterlogged areas within open stunted forests^[63], while their distribution was also recorded in open secondary forests^[64]. Occurrences of pitcher plants have been reported in heath forests, secondary forests, swamps, lowland forests, and post-mining lands, clearly indicating their preference for open habitats^[57]. Similarly, *Nepenthes* was also reported in roadside clearings and secondary bush vegetation, further emphasizing its association with open areas^[62]. Our findings about the distribution of *N. khasiana* mostly in hilly terrain with an open forest canopy of the Garo, Khasi, and Jaintia Hills of Meghalaya further match the previous studies on the distribution of most of the *Nepenthes* species. Overall, it suggests that *N. khasiana* consistently favors open or semi-open environments in various regions, indicating that the availability of light is a significant factor influencing their distribution.

Studies also exist regarding the landscape features, identical habitat conditions, and climatic factors that have some role in the species distribution. This is because landscape features greatly affect the variation of the microclimatic conditions of an area, which influences the morphological characteristics of the plant species^[65]. Comprehensive ecological studies on *Nepenthes talangensis* showed that the slope is an important environmental variable influencing distribution, with individuals typically found on

steep slopes (30–45%) from mid-slope to hill-slope habitats (i.e., slope gradient and orientation are part of habitat characterization)^[66]. A similar phenomenon was also reported in *Nepenthes* species on Mount Talang (West Sumatra, Indonesia), where landscape slope plays a key role in shaping their natural distribution and habitat preferences^[67]. In the present study, a similar distribution pattern was noted for *N. khasiana*, which was primarily found on sloping terrains instead of flat regions. The inclination towards slope habitats may be linked to beneficial microclimatic conditions such as enhanced drainage. This indicates that the characteristics of slopes significantly influence the spatial distribution of *N. khasiana*, like other *Nepenthes* species, and highlights the critical role of slope-related landscape features in its ecological niche and conservation strategies.

The study also found that the slope orientation affects the plant density. This variation might be because of spatial redistribution of sunlight, heat, water, and soil nutrients, resulting in the development of microclimatic conditions with different soil textures and nutrient distributions^[66,68–70]. Similar relationships between micro-topographic variation and vegetation associations have also been documented in Northeast India^[71]. In our study, the majority of the distribution sites were found facing toward the northwest orientation, further indicating the role of landscape features on the distribution pattern of pitcher plants in the Meghalaya state of India. Hence, the distribution of pitcher plants is affected by both slope orientation and elevation. A similar phenomenon was observed, where most of the pitcher plants were distributed in northwest-facing orientations, as north-facing slopes receive lower solar radiation, resulting in less xeric environmental conditions^[72]. Therefore, the present study demonstrates that *N. khasiana* exhibits a distinct preference for northwest-facing slopes at particular elevations. This highlights that the orientation of the slope, along with microclimatic conditions influenced by elevation, plays a crucial role in determining its spatial distribution in Meghalaya, India.

6. Conclusion

Overall, the present study clearly indicates that *N. khasiana* displays a distinct altitudinal distribution, primarily confined to mid-elevation montane areas ranging

from approximately 500 to 1,500 m above sea level. The species exhibits a marked preference for sloped terrains, where favourable microclimatic conditions, such as enhanced drainage and minimized disturbance, improve habitat suitability. Additionally, the prevalence of northwest-facing slopes underscores the significance of slope orientation for light intensity and moisture availability. Altogether, these results highlight that elevation, slope selection, and slope orientation collectively determine the spatial distribution and ecological niche of *N. khasiana* throughout its distribution range within the hilly regions of Meghalaya, India.

Author Contributions

Conceptualization, A.B. and P.S.; methodology, A.B.; software, A.B.; formal analysis, A.B.; investigation, A.B., S.G.M. and P.S.; resources, A.B., S.G.M. and P.S.; data curation, A.B.; writing—original draft preparation, A.B.; writing—review and editing, A.B. and P.S.; visualization, A.B.; supervision, A.B. and P.S. All authors have read and agreed to the published version of the manuscript.

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Data will be available on request from the authors.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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