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Table 1 to 3 are available in the Supplementary Files section.

Habitat dynamic and elevational gradient influences the phenotypic attributes of *Aconitum chasmanthum* Stapf ex Holmes

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Abstract

Aconitum chasmanthum Stapf ex Holmes is a critically endangered valuable herb with high medicinal potential. Phenotypic attributes of a particular plant species fluctuate across various climatic conditions and elevational gradients to withstand the demanding stressful settings. This study was intended to shed light on the effects of altitude and environmental factors on the morphological characteristics and phenology of *A. chasmanthum*. The quantitative morphological characters were studied in eleven natural populations across Kashmir Himalaya. The population of ACIII and ACIV have a short growing season and completed their phenological episodes within 135 days followed by ACVI. *A. chasmanthum* growing in open grassy slopes at an altitude of 3234m asl showed better growth and development in all morphological traits whereas plants growing at higher altitude ACIII (3712m asl) exhibited stunted growth and development in all the quantitative morphological traits viz (height; petiole, leaf, pedicel and rhizome dimensions). Linear regression analysis revealed a gradual reduction in morphological attributes with an increase in elevation. Pearson correlation value revealed a positive association between plant height and all other morphological characteristics. Principal component analysis (PCA), has shown that ACI, ACII and ACV had habitats, ecological conditions, and altitudes that were relatively more suited for the luxuriant growth and development of the endemic plant species *A. chasmanthum*. From the observations, it can be inferred that open moist grassy stable slopes are better suited for its growth than open moist rocky slopes and banks of small alpine rivulets. This study offers a thorough description of phenotypic variation with environmental circumstances and suggests a habitat that is suited for the sustained cultivation of this significant medicinal plant species in the Kashmir Himalaya.

Keywords Distribution · Conservation · Habitat variability · Morphology · Phenology · Threats

Introduction

Alpine habitats are characterized by abrupt environmental changes over small distances [1]. The alpine landscape is naturally fragmented and exhibits significant spatial variability as a result of the compression of climatic living zones over condensed geographical distances. The high biodiversity of alpine plants is a result of the variety of microhabitats, but it also causes geographic isolation between populations and constrained gene flow [2, 3]. In addition, plants at higher elevations must contend with reduced air pressure, lower temperatures, a shorter vegetative

phase, a smaller window for reproduction, as well as greater snowfall and weather-related severe occurrences [4,5]. Plants can either genetically adapt to local circumstances to live in such diverse and challenging environments, or they can respond to environmental variability through phenotypic plasticity [6, 7].

Local adaptation improves a population's success in its specific habitat [8], but phenotypic variability allows a single genotype to exhibit several phenotypes in response to environmental factors [9-11]. Since plants cannot move and must adapt to changing environmental conditions, phenotypic variability permits organisms to respond quickly to a changing environment [10, 6] because it allows quick adaptation to a temporally highly changeable environment. Phenotypic adaptability is also expected to occur more often at higher elevations, guaranteeing the survival of alpine plants [2, 12]. Though not always beneficial, variability can sometimes be nonadaptive and have a neutral or worse impact on fitness [13]. Genetically fixed features may be preferred in some situations, which are often temporally stable [14, 15], due to the costs and restrictions associated with the development and maintenance of variability [16]. To forecast how plants will adapt to future climate change, it is necessary to understand whether and how much a species can adapt phenotypically to a changing environment. If phenotypic modifications are restricted, plants would either need to quickly adapt to the new conditions genetically or move to follow the conditions they are now accustomed to [17]. If a climatic change occurs quickly, the fitness of locally adapted plants may fall fast, increasing the likelihood of local extinction, particularly for isolated, inbred, and apomictic species [18, 19, 17].

One of the most effective "natural experiments" for examining how the biota responds to geophysical factors like low temperatures are to use of altitudinal gradients [20]. Plant physiologists, ecologists, and paleobotanists are all very interested in the connection between altitude and plant form. High-altitude species typically differ from closely similar species at lower elevations in terms of morphology and physiology. According to [21], altitude also has a significant impact on the morphology and physiology of leaves within a species.

The phenology of any plant species is strongly dependent on climatic conditions at higher elevations, particularly in mountain environments [22, 23]. To ensure the reproductive success of plant species, several environmental elements, including elevation, temperature [24, 25], soil moisture, photoperiod, and snowmelt, influence floral phenology [1, 26]. Complex biotic elements (flora and fauna) and abiotic elements (soil, temperature, precipitation, moisture, etc.) are provided by the elevational gradient, which experiences significant variations with elevation [20]. As a result, the physical complexity in the mountains promotes speciation and increases isolation, leading to a rise in species richness, beta diversity, and turnover with elevation [20, 27, 28].

Aconitum chasmanthum Stapf ex Holmes (Ranunculaceae), commonly known as Gaping Monkshood, Vatsanabha, locally known as Mohand, Mohand posh, Mohand gurd is a biennial herb, having an erect stem, reaching 60 to 90 cm in height [29], numerous leaves and hermaphrodite flowers aggregated in racemes. The IUCN has classified it as severely endangered [30], with an extremely limited range. Native to Pakistan and India, it can grow in the western Himalayas. It is most common in the subalpine and alpine zones, from Chitral and Hazara between 2300 and 4300 m [31] to Kashmir and Himachal Pradesh between 2100 and 3600 m asl [32, 29]. It prefers light (sandy) soils with mildly alkaline (basic soils), but it can also grow in medium (loamy) and heavy (clay) soils. It prefers moist but well-drained soils.

Aconitum chasmanthum is a critically endangered medicinal plant with unparalleled therapeutic properties and is widely used in numerous Southeast Asian nations [33]. *A. chasmanthum* is associated with various biological activities as it has a large number of phytochemicals. Locals use its rhizome to treat diseases such as fever, rheumatism, cough, asthma, and snake bites [34, 35], and after being combined with butter oil, its rhizome powder is used as an ointment to treat boils and abscesses [36]. It serves as an appetizer to soothe pain and inflammation [37], as well as for cardiovascular disease, anodyne, anti-diabetic, tonsillitis, astringent, diarrhoea, neurasthenic, cold and cough purposes [38-40]. Its rhizomes have been documented for various microbial activities including antifungal, insecticidal, antibacterial [31] and antioxidant effects [41].

Materials and Methods

To explore phenotypic plasticity and phenology under various environmental and altitudinal conditions, a dynamic approach was adopted in the current study. Data on several morphometric traits were collected to uncover features of phenotypic variability. The survey was carried out from May 2019 to October 2021.

Exploration, collection and documentation

Different regions of the Kashmir Himalaya (India) were extensively surveyed and explored to select different study sites in the region. Eleven sites: Bangus valley-I (2913m asl), Bangus valley-II (3214m asl), Pahalgam- I (3712m asl), Pahalgam-II (3642m asl), Gulmarg (3234m asl), Farhad's Canal Ganderbal (3673m asl), Maloodh Ganderbal-I (3457m asl), Maloodh Ganderbal-II (3256m asl), Gurez (3728m asl), Razdhan Pass-I (3270m asl), Razdhan Pass-II (3423m asl), were chosen to explore the variation in phenotypic traits based on their accessibility, habitat characteristics, and prevailing environmental conditions along an altitudinal gradient. The geographic location of the chosen sites is shown on the table 1 and also on map (Fig. 1). Given adequate consideration for the critically endangered status, vigorous adult blooming plants of *Aconitum chasmanthum* Stapf ex Holmes were very carefully picked from several study sites. The specimen was identified and authenticated by Dr. Anzar Ahmad Khuroo at the Centre for Biodiversity and Taxonomy (CBT), Department of Botany, University of Kashmir, Hazratbal, Srinagar. A voucher specimen was submitted under accession number (2939-KASH) has been deposited at the Kashmir University Herbarium (KASH). From each study site, 10 to 15 specimens of the species were randomly selected and tagged. Between May 2019 to October 2022, the tagged individuals underwent routine monitoring. The related species of the chosen location, vegetation type, habitat, geo coordinates, and heights were noted (Table 1).

Phenology

Initiation, duration and completion of various phenophases viz sprouting of underground rhizome, floral bud formation, anthesis, peak flowering, seed maturation and complete senescence of aerial parts were undertaken in eleven natural populations. 15 individuals were randomly selected from each population and marked with aluminum tags and monitored during the growing seasons of three consecutive years (2019, 2020 and 2021).

Species Morphology and Phenotypic Variability

At regular intervals of 10-15 days, the population's randomly chosen members of the population were continuously monitored. Variations in morphological characteristics, such as plant height, rhizome, petiole, leaf, and pedicel dimensions were noted. To identify the places where this species grows best, we performed linear regression analysis to ascertain the link between several morphological features along the altitudinal gradient. To assess the morphological features in connection with habitat dynamics, principal component analysis (PCA) was used.

Statistical analysis

Microsoft Excel was used to calculate the average and standard error for LSD and Tukey's test (one-way ANOVA) to compare the significant level (MS-office-16). To identify the best habitat for improved growth and development, the link between distinct morphological traits across various environmental conditions and altitudes was examined using linear regression and Pearson's correlation coefficient analysis. To display the lowest, median, and maximum values of each variable, box plots were created. The coefficient of variation (CV) for each trait was calculated as a complementary index to evaluate intraspecific variation using the formula: $CV = \text{standard deviation} / \text{mean} \times 100$. The population's phenotypic plasticity index (PPI) was determined using the formula: $PPI = (\text{maximum mean} - \text{lowest mean}) / \text{maximum mean}$ [42, 43]. To evaluate the phenotypic characteristics with various habitat circumstances, principal component analysis (PCA) was used. The PCA was examined using Origin-Pro 2019b 64 software, and the correlation was discovered using R (version 4.1.2; 64-bit) software. Data was gathered for 10-15 plants from each community to evaluate the variation in phenotypic characteristics. A Canon DSLR (1300D), and a Realme X3 superzoom smartphone camera was used to shoot the pictures.

Results

Distribution

Aconitum chasmanthum Stapf ex Holmes is locally known as Mori, Mohand, Mohand posh, Mohandgurd. In the Kashmir Himalaya, *A. chasmanthum* is distributed in the alpine and sub-alpine regions of Ganderbal (Farhad Kul, Maloodh, Sonmarg, Vishansar), Baramulla (Apharwat Gulmarg, Kangdoori Gulmarg, Khilanmarg Gulmarg, Uri), Bandipora (Razdhan Pass, Gurez, Chorwan Gurez, Khupri Gurez, Dahinala Gurez), Anantnag (Rayil lake, Posh phatri, Mahaganesh top), Kupwara (Bangus Valley), Shopian (Hirpora Wild Life Sanctuary), Srinagar (Dachigam National park), Budgam (Hapatkhod Yusmarg) at altitudes ranging from 2900-4000 m altitudes. The northeastern part of the Kashmir Himalaya contains the maximum population of *A. chasmanthum*, and the selected areas of the distribution pattern are shown in the map (Fig.1). In the Kashmir Himalaya, it is mostly distributed along the banks of small alpine rivulets, moist damp slopes, open grassy and moist grassy slopes, and open meadowlands and open moist meadowlands (Table 1). It grows luxuriantly in open moist; but well-drained slopes and is strongly associated with species like *Bergenia ciliata*, *Iris* spp., *Fragaria* spp., *Dryopteris* spp., *Swertia* spp., *Geranium* spp., *Podophyllum hexandrum*, *Rumex* spp., *Epilobium* spp., *Jurinea* spp., *Fragaria* spp., *Juniperus* spp., *Meconopsis aculeata*, *Primula* spp., *Centella* spp., *Indigofera* spp., *Centurea* spp., *Ranunculus* spp., *Geranium* spp., *Polygonum* spp., *Saussurea costus* and *Thalictrum* spp. etc.

Threats faced

Aconitum chasmanthum faces the onslaught of extinction from the region due to various biotic and abiotic factors and is facing the threat of extinction in its natural habitat (Fig.2). According to the IUCN Red List of threatened species, *A. chasmanthum* has been assessed as critically endangered (IUCN 2015). The main threats it faces in its natural habitat include a long period of dormancy (>5 months) due to its hard seed coat and the reduced light access of being buried under the litter of other species (photoblastic nature), as well as a long period of winter [44]. In snowfall, the seeds of this plant experience a long period of dormancy. The seeds are at risk of being washed away by severe rains and snow avalanches from their native environment, thus exposing them to adverse environmental conditions. Their survival rates and abundance are significantly affected by competition with other species after the germination of disseminated seeds [45]. While the plant, the entire species is rooted, which hinders the regrowth of the species by preventing flowering and seed development. *A. chasmanthum* mostly thrives in open, damp, rocky slopes, making it susceptible to landslides, avalanches, and other natural disasters that might wipe out its native populations. Grazing and tramping of seedlings by cattle and overharvesting lead to the loss of their natural populations [45]. The construction of tourism huts and high-altitude roads has led to habit fragmentation (Fig. 2a–c). Furthermore, the species has a highly specialised ecological niche that may potentially restrict its range of expansion and dispersion [45]. Beetles and aphids (Fig. 2 d,e,f) are two additional possible threats to the species since they feed on floral buds and consume the reproductive section of the plant, further lowering the species reproductive capacity [35] and the same threats has been reported for *A. violaceum* [46] from Ladakh Himalaya.

Phenological events

The phenophase of *A. chasmanthum* starts from the germination of an underground rhizome. The specific phenophases vary within different populations. The population ACIII and ACIV exhibited a short growing season and complete their life cycle within 135 d (Germination of the underground rhizome started on the 2nd week (wk) June and showed complete senescence on the 4th wk of September) followed by the population ACVI, whereas the ACI and ACII populations possessed a long growing season of 178 d. The underground rhizome started growing in the 4th wk of April and completed the senescence of aerial parts in the 3rd or 4th wk of October. The detailed phenophases were summed up in Fig. 3. The production of floral buds, which partially overlaps with the sprouting process. Anthesis begins around the first week of July and lasts till the first week of September.

Species morphology and phenotypic variability

The morphological characteristics of *A. chasmanthum* are summarised in (Table 2, Fig. 4). At various elevations and climates, the phenotypic traits of *A. chasmanthum* exhibited substantial diversity. These phenotypic variations were observed at 11 particular locations (Table 1). The following morphological traits were evaluated for phenotypic variability: average plant height, average rhizome length, average rhizome width, average petiole length, average leaf length, average leaf width, average pedicel length, average flower length, average flower width, average follicle length, average seed length, and average seed width (Table 3). Populations from the chosen sites had noticeable

variances in phenotypic features, altitude, and environmental factors. The average plant height varies from 26.62 ± 1.23 cm to 85.8 ± 2.40 cm, the fresh rhizome length is 2.57 ± 0.25 cm to 5.75 ± 0.50 cm, the fresh rhizome girth is 2.62 ± 0.15 cm to 5.08 ± 0.29 cm, the basal petiole length 4.58 ± 0.44 cm to 10.75 ± 1.15 cm, the basal leaf length 3.21 ± 0.31 cm to 8.02 ± 0.62 cm and the basal leaf width 4.79 ± 0.43 cm to 10.05 ± 0.5 cm (Table 3).

Additionally, the apical leaf length ranges from 1.275 ± 0.20 cm to 2.08 ± 0.2 cm, the width of the apical leaf is 0.81 ± 0.15 cm, to 1.62 ± 0.32 cm and the leaf number per plant is 9.25 ± 0.77 cm to 22.4 ± 1.47 cm (Table 3). The average floral number per plant varied from 14.0 ± 0.46 cm to 33.8 ± 2.22 cm, while the average pedicel length varied from 3.31 ± 0.44 cm to 4.12 ± 0.42 cm (Table 3). Most quantitative morphological features exhibited an inverse relationship with altitude (i.e., they displayed a steady decline as altitude increased). The examined morphological traits differ greatly among the chosen groups. Along with the altitude, the various populations displayed a great deal of morphological variation. The ACV population has the highest values for almost all physical features when compared to the other populations. The Bangus valley (ACI and ACII) populations showed morphological characteristics almost similar to the Gulmarg population, followed by the Razdhan populations (ACX and ACXI), while the Rayil Phalgham populations (ACIII and ACIV) exhibited the lowest values for morphological features.

Morphological attributes showed high variation (Fig. 5 and Fig. 6). Coefficient of variation (CV) was 36.18% for plant height, 27.12% for fresh rhizome length, 21.68% for fresh rhizome girth, 32.8% for basal petiole length, 34.79% for basal leaf length, 29.58% for basal leaf width, 17.81% for apical leaf length, 26.51% for apical leaf width, 6.9% for pedicel length, 29.26% for flower number and 35.55% for leaf number. All morphological characters showed significant variation among subpopulations. Phenotypic plasticity index for 11 morphological characters is shown in Fig. 7. High phenotypic plasticity was observed for plant height (0.68), fresh rhizome length (0.55), fresh rhizome girth (0.48), basal petiole length (0.57), basal leaf length (0.59), basal leaf width (0.52), apical leaf length (0.39), apical leaf width (0.5), pedicel length (0.2), flower number (0.58) and leaf number (0.59).

Plant height and other quantitative features exhibited a positive relationship (i.e., individual plants with large height have larger growth forms for other phenotypic traits such as rhizome, leaf dimension, leaf number and flower number etc.). There was a negative correlation between plant height and elevation ($r^2 = 0.75415$), and a positive correlation between plant height and fresh rhizome length ($r^2 = 0.92628$), plant height and basal petiole length ($r^2 = 0.84399$), plant height and basal leaf length ($r^2 = 0.90731$), plant height and flower number ($r^2 = 0.96386$), plant height and leaf number ($r^2 = 0.87582$) as shown in (Fig. 5). Almost all quantitative phenotypic variables (such as rhizome diameter, leaf dimension, leaf number, inflorescence length, flower number, etc.) were positively correlated according to Pearson's correlation coefficient (Fig. 8). According to Principal Component Analysis (PCA), physical characteristics gradually get smaller as the altitude increases and vice versa (Fig. 8). The first three PCA's explained 98.4% of the total variance (92.7, 3.8 and 1.9% respectively). The population growing at Gulmarg, Bangus Valley and Razdhan Pass grew most luxuriantly and showed the highest phenotypic traits, whereas the population growing at high elevation (Rayil Phalgham) showed a decrease in size of all phenotypic traits compared to other populations, separating them from the rest of the other populations of the study site.

Discussion

Plants growing in vast elevational gradients in mountains endure significantly diverse abiotic and biotic environments that alter dramatically over relatively short vertical distances. Because both the biotic and abiotic elements of elevation in mountains are essential for plant growth, they cannot be easily distinguished from each other. Because of this, studies on the phenotypic variation of plant species in mountains have focused on the elevational gradient [2, 47, 48, 49, 50, 51, 52, 53]. Plants can adapt locally and respond to elevational changes depending on their morphological and physiological flexibility [54]. Species spread over broad elevational ranges exhibit intraspecific morphological variations along elevational gradients. Shorter stems, fewer blossoms, and bigger flowers are all characteristics of plants that grow at higher elevations than those that do not [55, 56, 57, 58]. Along with an increase in elevation, plants also have better flower lifespan plasticity [59], as well as increased clonality [47]. Understanding the function of natural selection in plant adaptation to alpine settings and plant phenotypic responses to such conditions requires knowledge of differences in morphological features and plant performance in wild populations over elevational gradients [60, 61].

The extensive geographic spread and morphological variability of the *Aconitum* Genus make it significant for systemic research. Hadi et al have noted a high degree of phenotypic variability in the physical characteristics of *Aconitum violaceum* [62]. In the current study, *Aconitum chasmanthum* of the Kashmir Himalaya was found to have a high degree of morphological diversity in terms of the length of the fresh rhizome, the girth of the fresh rhizome, the length of the basal petiole, the length of the basal leaf, the width of the basal leaf, the length of the apical leaf, the width of the apical leaf, the length of the pedicel, the number of leaves per plant and flower number per plant. In terms of morphological characteristics, the impact of the altitudinal gradient was observed. High phenotypic diversity was observed in *A. chasmanthum* from the Kashmir Himalayan area, which was collected from an altitudinal range of 2913-3728m asl. Plants thriving at elevations ranging from 2900 to 3300 m asl (Gulmarg and Bangus Valley populations) were substantially more robust and diversified in all morphological traits. There was significant variation in phenotypic characteristics, and there was a general tendency toward a linear decline in plant features with elevation. As the altitude increases, there is a significant variation in the height of the plants. This is consistent with the observations made by [1, 63, 64, 62, 65] who also noted a reduction in plant size as an adaptation to the rising altitude. Increasing altitude causes plants to grow more slowly, helping them use resources more effectively in harsh climates [66]. This may be advantageous for the species since the stem shortening helps plants escape the negative impacts of strong winds [67], and the ability of plants to supercool at high altitudes is increased by smaller cells and intercellular gaps [68]. The physical traits of *A. chasmanthum* populations growing at various elevations in the Kashmir valley exhibited both a direct and a negative association with the altitude; significant phenotypic variation was also discovered within and between individuals of these populations.

The CV is a common and basic phenotypic variation metric used in many investigations. In an altitudinal gradient of 815m, we found a high CV for plant height (36.18%), basal petiole length (32.8%), basal leaf length (34.4%), basal leaf width (29.58), flower number (29.26), and leaf number (35.66). With comparison to [69], who observed 17.37%, 25.58%, 18.02%, and 17.19% of CV in regard to leaf length, leaf width, fruit length, and fruit width in wild

populations of *Vaccinium meridionale* over an altitudinal gradient of 2357-3168 m asl, with an altitudinal difference of 811m. In another study on *M. alba* conducted in the trans-Himalayan region (Ladakh), [70] found high CVs for leaf length (26.6%), leaf breadth (26.2%), petiole length (32.2%), and leaf area (50.3%) from an altitudinal range of 2815-3177m asl in a very small altitudinal gradient of 362 m. Phenotypic plasticity among populations was also analysed using phenotypic plasticity index (PPI). PPI is a popular plasticity measure that is both simple and reliable [43]. All morphological characteristics, particularly the plant height, basal leaf length, flower number and leaf number, showed high plasticity. In reaction to environmental change, plants either passively limit their growth in low resource environments or actively boost resource acquisition in each habitat with sufficient resources [71, 72]. Consequently, when altitude varies, the climate also alters, which causes variations in the way that resources are acquired. These differences in pattern are then seen in phenotypic.

Phenology, the study of recurring seasonal natural phenomena, can assist scientists in comprehending changes in Alpine plants brought on by the effects of global warming [73] and can have a significant impact on a species reproductive success [74]. Unquestionably, one of the best methods to see and understand how a specific plant species interacts with and responds to changing environmental conditions is through the study of phenology. Because it affects pollinator attraction and reproductive synchrony with possible mates [75], flowering phenology is particularly significant [76]. In particular, flowering phenology is significant as it affects pollinator attraction [76] and reproductive synchrony with possible pollinators [75]. Altitude mostly controls the phytophenological phases by causing temperatures to drop by around 0.6 °C per 100m [77]. By regulating synchronization to, and subsequent sensitivity to floral herbivores and seed predators, flowering timing may also have a significant impact on reproductive success [78]. Therefore, it is clear that phenological events are very beneficial in establishing conservation strategies for species that are threatened as well as creating procedures for commercial cultivation [79, 80]. Flowering is the longest phenophase in the species out of all phenophases. Due to the prolonged blooming time, there is a greater likelihood that an individual will have a large number of partners available to act as both pollen givers and receivers, maximising their reproductive potential.

Conclusion

The current study found that *A. chasmanthum* populations in the Kashmir Himalaya differ significantly in terms of physical characteristics. Along an altitudinal gradient, *A. chasmanthum* generally showed substantial phenotypic variation. The findings indicated that even a slight rise in altitude created significant challenges for plants trying to live in the Kashmir Himalayan environment. According to this study, phenotypic plasticity helps sustain observed phenotypic variance to some extent. To forecast how plants will react to future environmental changes, including those brought on by global warming, it is essential to comprehend the role played by phenotypic plasticity. *A. chasmanthum* in the Kashmir Himalaya's phenotypic plasticity might be used as a model system to explore how plants will adapt to changing environmental conditions in the future. This work also has evolutionary importance as it offers a fundamental overview of the phenotypic variation of *A. chasmanthum* in the Kashmir Himalayan area for future research.

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Author contributions SR: investigation, writing - review, editing and analysis. AH: investigation, writing - review, editing and analysis. AH, SR: draft preparation, review. ZAK: validation, methodology, software, data curation. MM: draft preparation and review. NAW: investigation, validation, data curation. SA: Assisted in field survey, characterization

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Data Availability:

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable, as this is plant-based study.

Consent for publication

Not applicable

Plant reproducibility:

Plant material of *Aconitum chasmanthum* Stapf ex Holmes Clarke were selected from 11 locations in the Kashmir Himalaya, India: Bangus valley-I (2913m asl), Bangus valley-II (3214m asl), Pahalgam- I (3712m asl), Pahalgam-II (3642m asl), Gulmarg (3234m asl), Farhad's Canal Ganderbal (3673m asl), Maloodh Ganderbal-I (3457m asl), Maloodh Ganderbal-II (3256m asl), Gurez (3728m asl), Razdhan Pass-I (3270m asl), Razdhan Pass-II (3423m asl). The specimen was identified and authenticated by Dr. Anzar Ahmad Khuroo at the Centre for Biodiversity and Taxonomy (CBT), Department of Botany, University of Kashmir, Hazratbal, Srinagar. A voucher specimen was submitted under accession number (2939-KASH) has been deposited at the Kashmir University Herbarium (KASH) for future reference.

The studied species (*Aconitum chasmanthum* Stapf ex Holmes Clarke) is indeed enlisted in both IUCN Red List of threatened Species and CITES Appendices. To minimize any impact on natural populations, phenotypic observations and measurements were conducted on living plants in their natural habitats without damaging or removing plant parts. Seed-related data were recorded only after natural seed dispersal. No destructive sampling of individuals was undertaken for the purposes of this study. All field investigations and experimental procedures were carried out in accordance with applicable institutional, national, and international guidelines and regulations governing biodiversity research and the conservation of threatened plant species. The research was observational in nature and focused on documenting phenotypic variations across altitudinal gradients. As no protected plant material was collected, transported, traded, or subjected to destructive experimental procedures, the study posed negligible risk to

the species or its habitat. Necessary permissions for field access and research activities were obtained from the relevant authorities prior to conducting the study.

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Fig. 1 Map depicting collection sites and study area of *Aconitum chasmanthum* Stapf ex Holmes

Fig. 2 Threats faced by *Aconitum chasmanthum* Stapf ex Holmes in its natural habitat (a) high altitude road construction material and destroying the natural population and even making it more susceptible to landslides (b) Long dry spells drying out the populations (c) habitat fragmentation by high altitude road construction (d) larvae feeding on the seed pods and seeds destroying its sexual potential (e) aphids (*Macrosiphum* spp.) feeding on floral parts (f) larvae feeding on floral parts.

Fig. 3 Phenogram showing phenology of *Aconitum chasmanthum* Stapf ex Holmes in 11 different populations across Kashmir Himalaya during 2021.

Fig. 4 Morphology characteristics of *Aconitum chasmanthum* Stapf ex Holmes (a) habit (b) habitat (c) inflorescence (d) seed pods (e) seeds (f) sprouted rhizomes

Fig. 5 Linear regression analysis between several morphological features of *Aconitum chasmanthum* Stapf ex Holmes (a) plant height vs elevation (b) plant height vs basal pedicel length (c) plant height vs basal leaf length (d) plant height vs flower number (e) plant height vs leaf number (f) morphological attributes of *A. chasmanthum*

Fig. 6. Box plot depicts the interquartile range; centre horizontal range represents the median. Line extending out of the box indicated the upper and lower quartile. Black coloured points represent the outlier of 11 morphological characters of in 11 populations of *Aconitum chasmanthum* Stapf ex Holmes

Fig. 7 Phenotypic plasticity index for 11 morphological characters of *Aconitum chasmanthum* Stapf ex Holmes (Plant height (PH), Fresh rhizome length (FRL), Fresh rhizome girth (FRG), Basal petiole length (BPL), Basal leaf length (BLL), Basal leaf width (BLW), Apical leaf length (ALL), Apical leaf width (APW), Pedicel length (PL), Flower number (FN), Leaf number per plant (LN).

Fig. 8 Scattering plot demonstrating Pearson's correlation matrix for quantitative phenotypic traits among different populations of *Aconitum chasmanthum* Stapf ex Holmes (*** $p < 0.000$, ** $p < 0.001$, * $p < 0.01$)

Fig. 9 Principal component analysis (PCA) of morphological characteristics of *Aconitum chasmanthum* Stapf ex Holmes across different study sites. Plant height (PH), Fresh rhizome length (FRL), Fresh rhizome girth (FRG), Basal petiole length (BPL), Basal leaf length (BLL), Basal leaf width (BLW), Apical leaf length (ALL), Apical leaf width (APW), Pedicel length (PL), Flower number (FN), Leaf number per plant (LN).

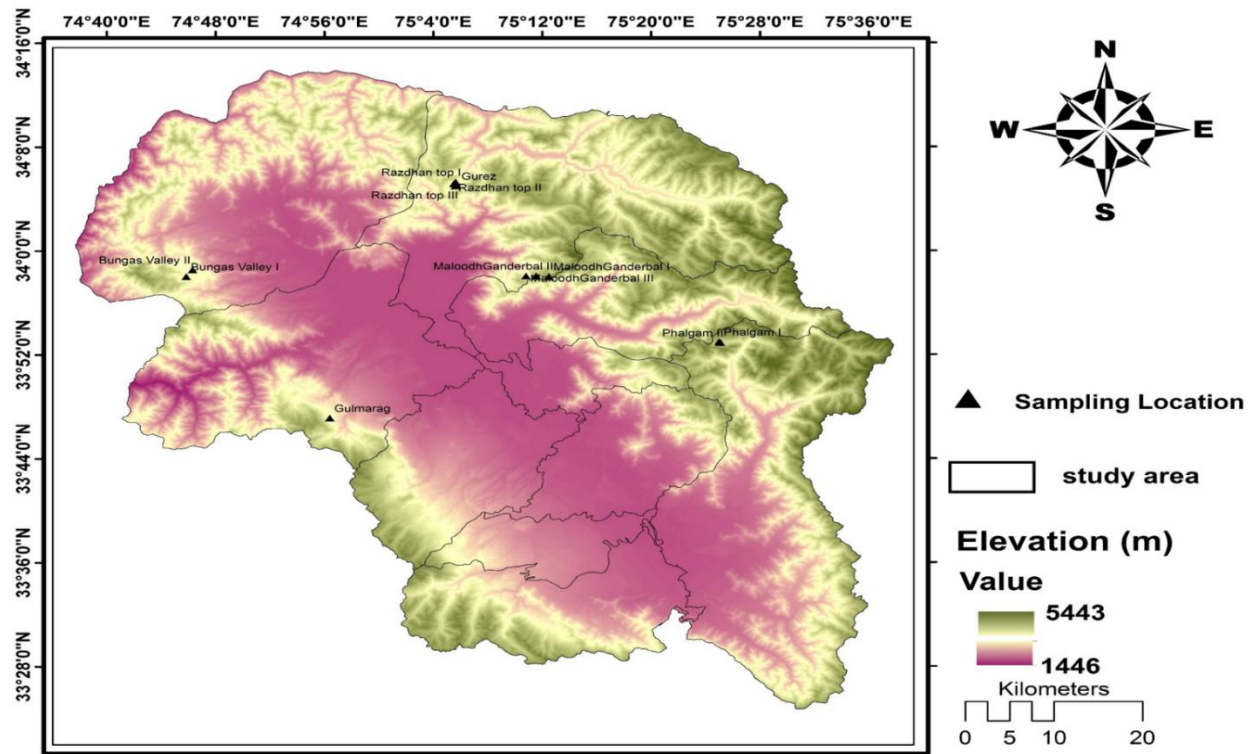


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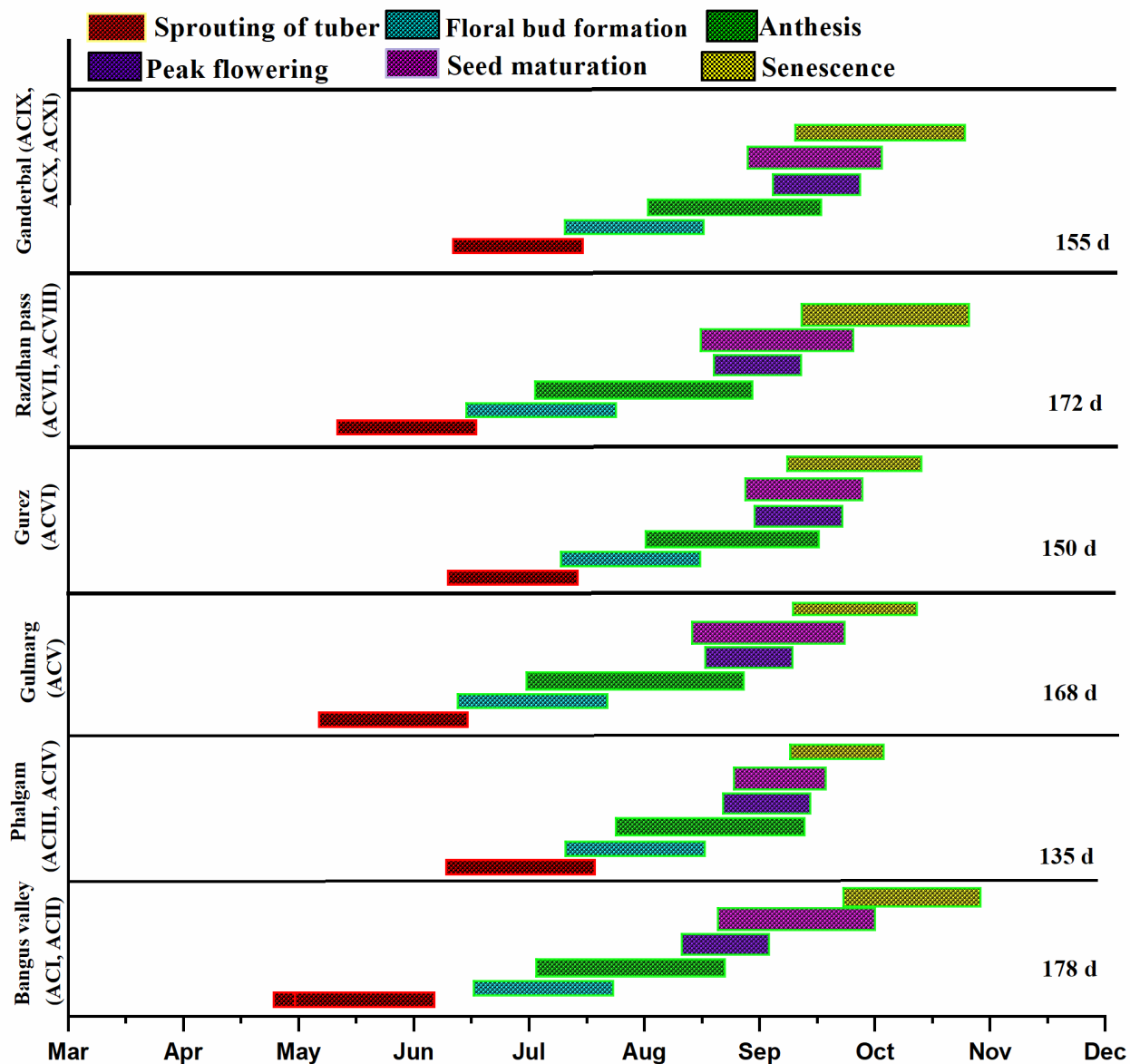


Fig. 3. Phenogram showing phenology of *Aconitum chasmanthum* Stapf ex Holmes in 11 different populations across Kashmir Himalaya during 2021.

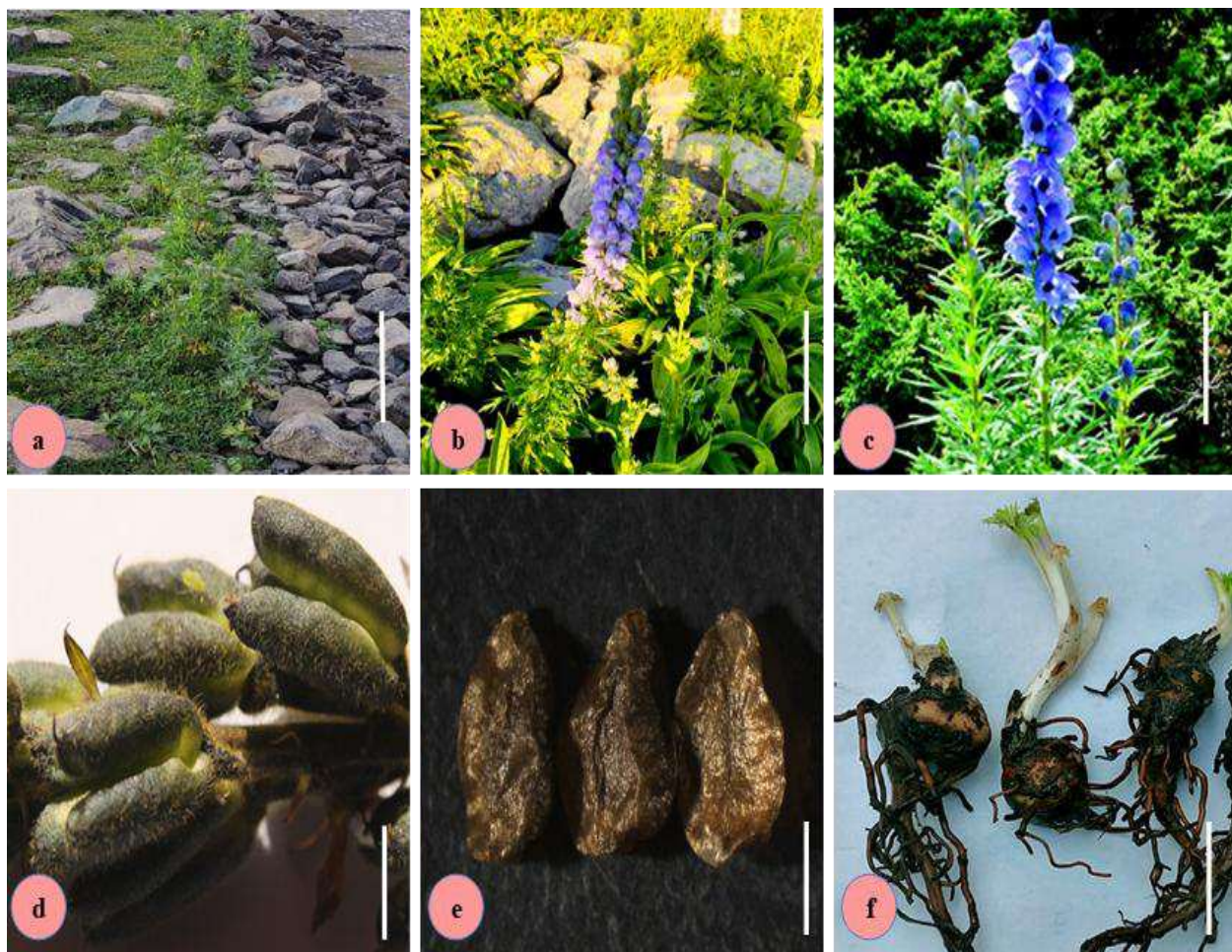


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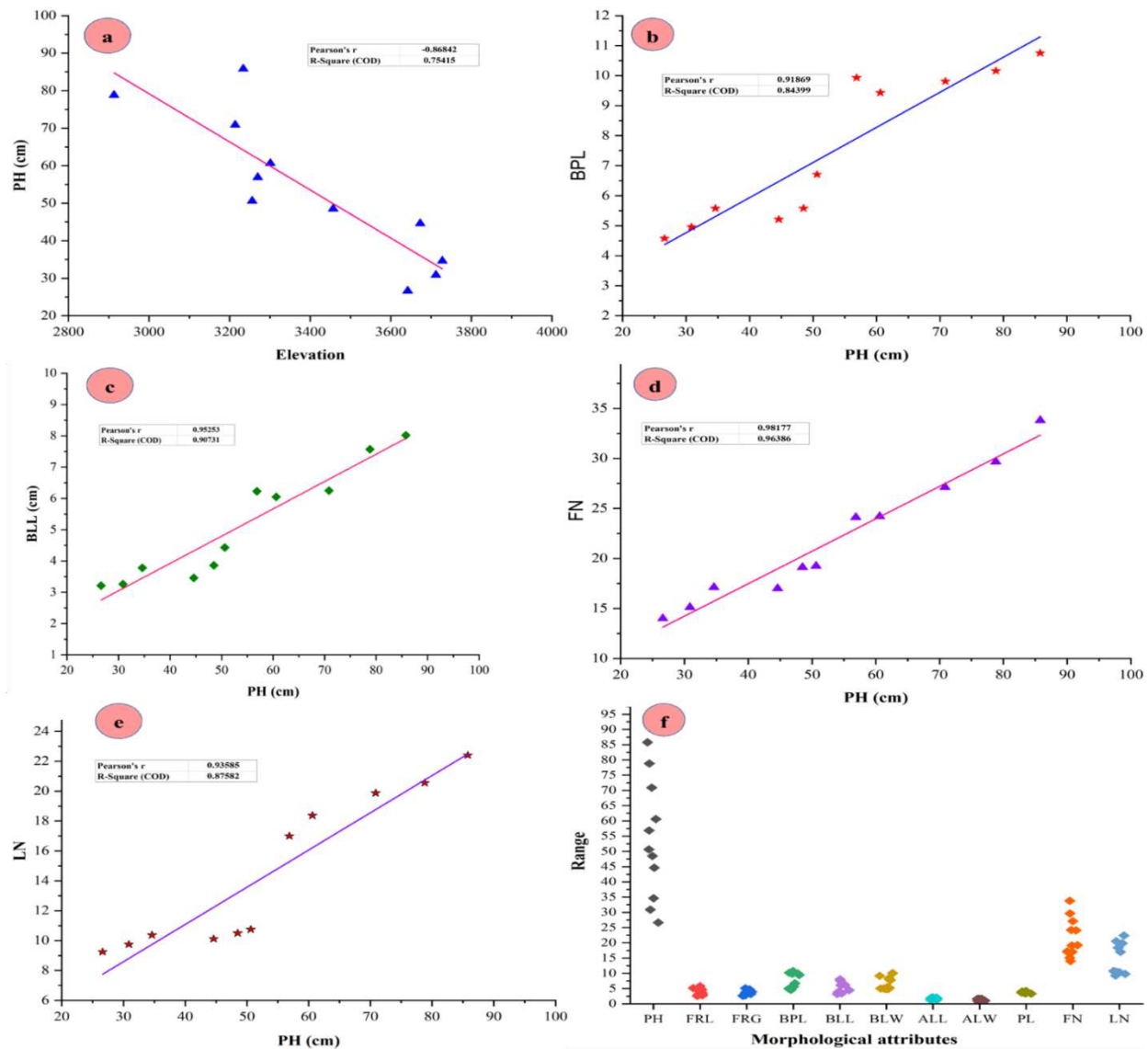


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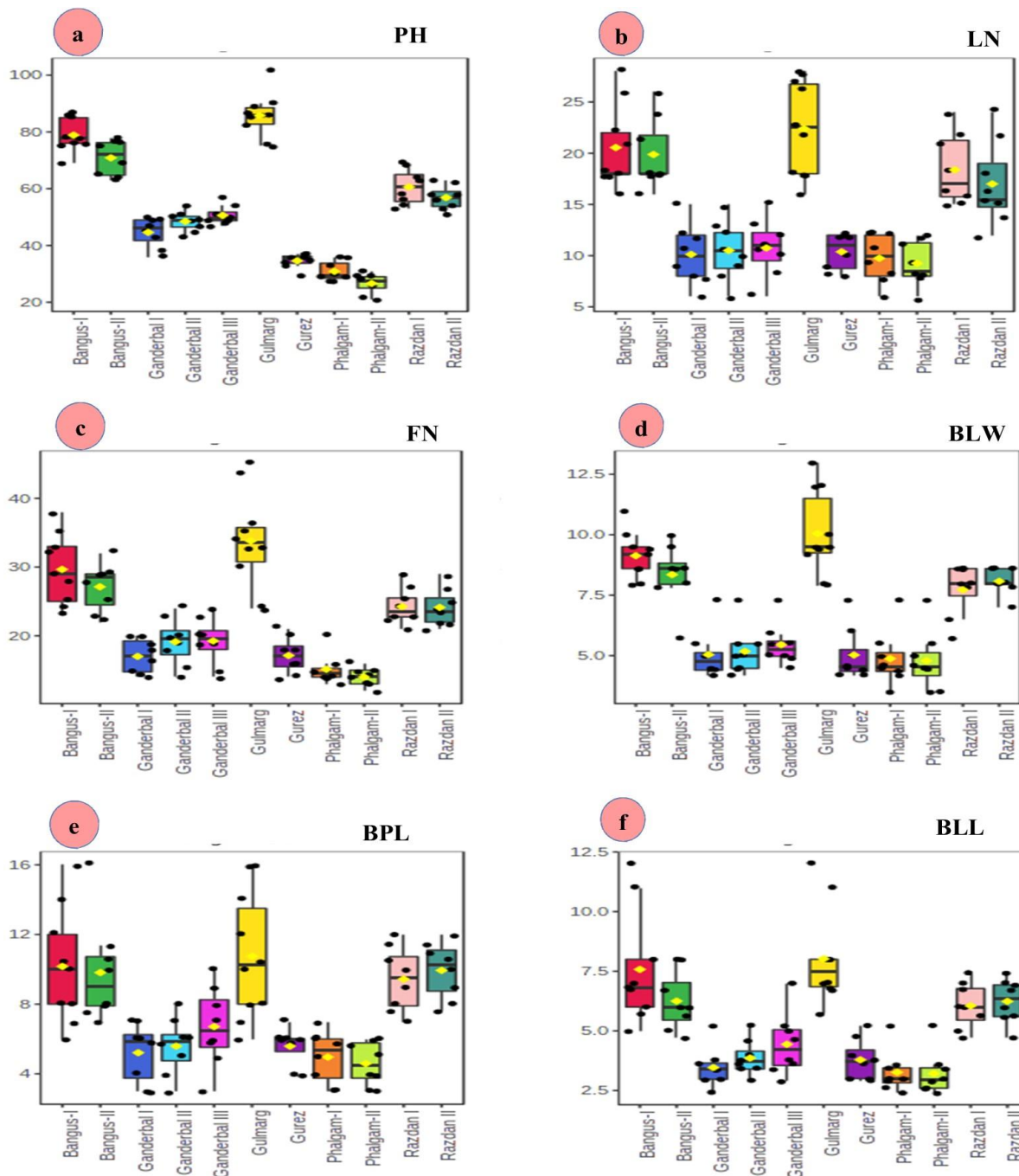


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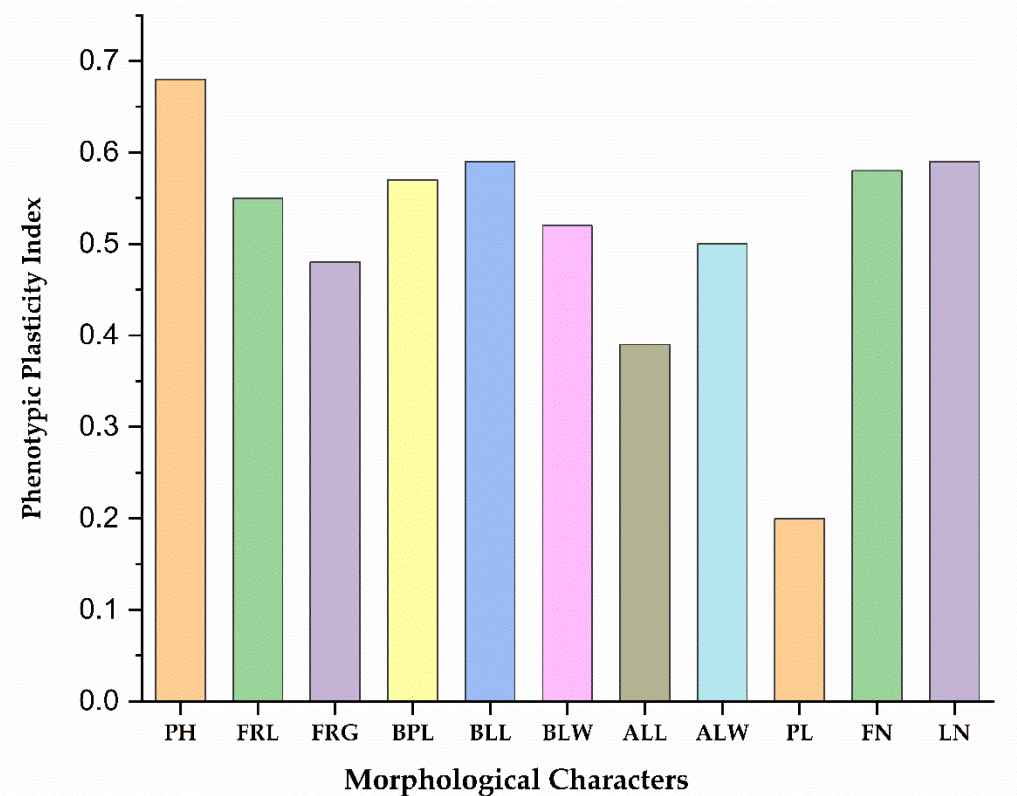


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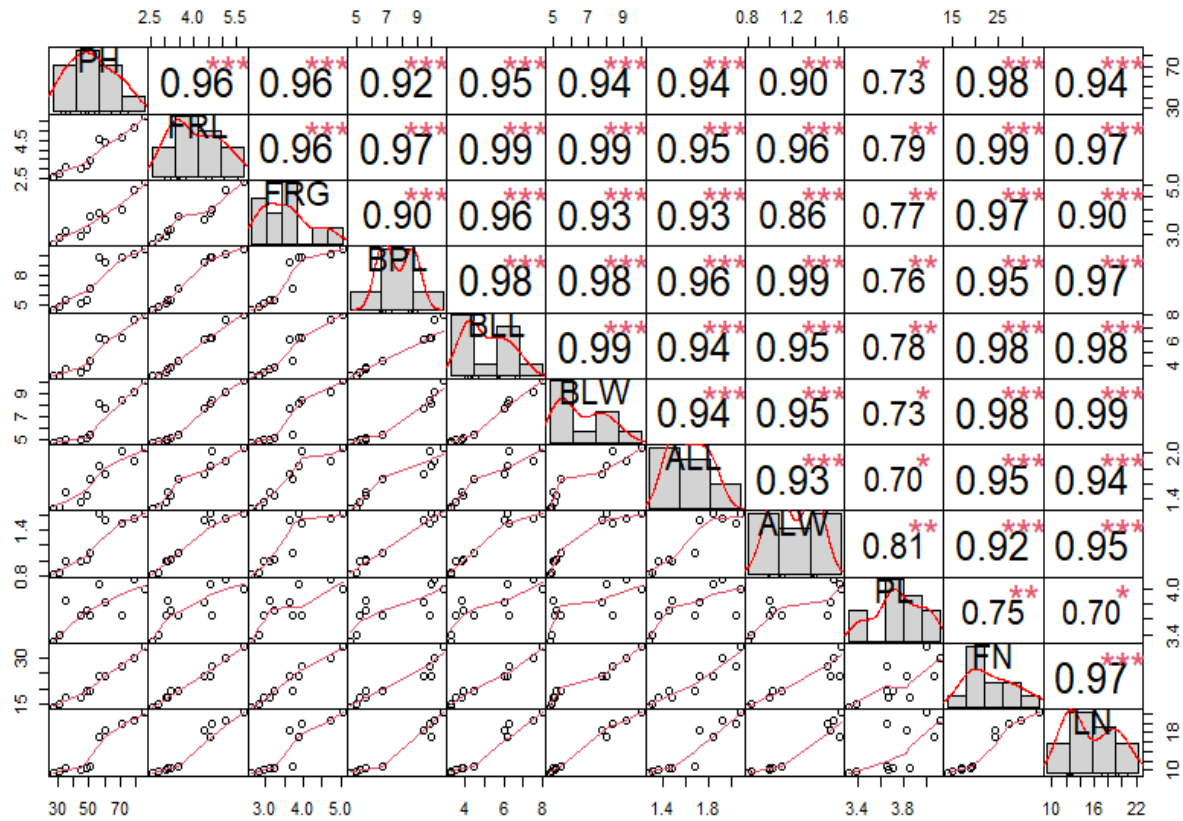


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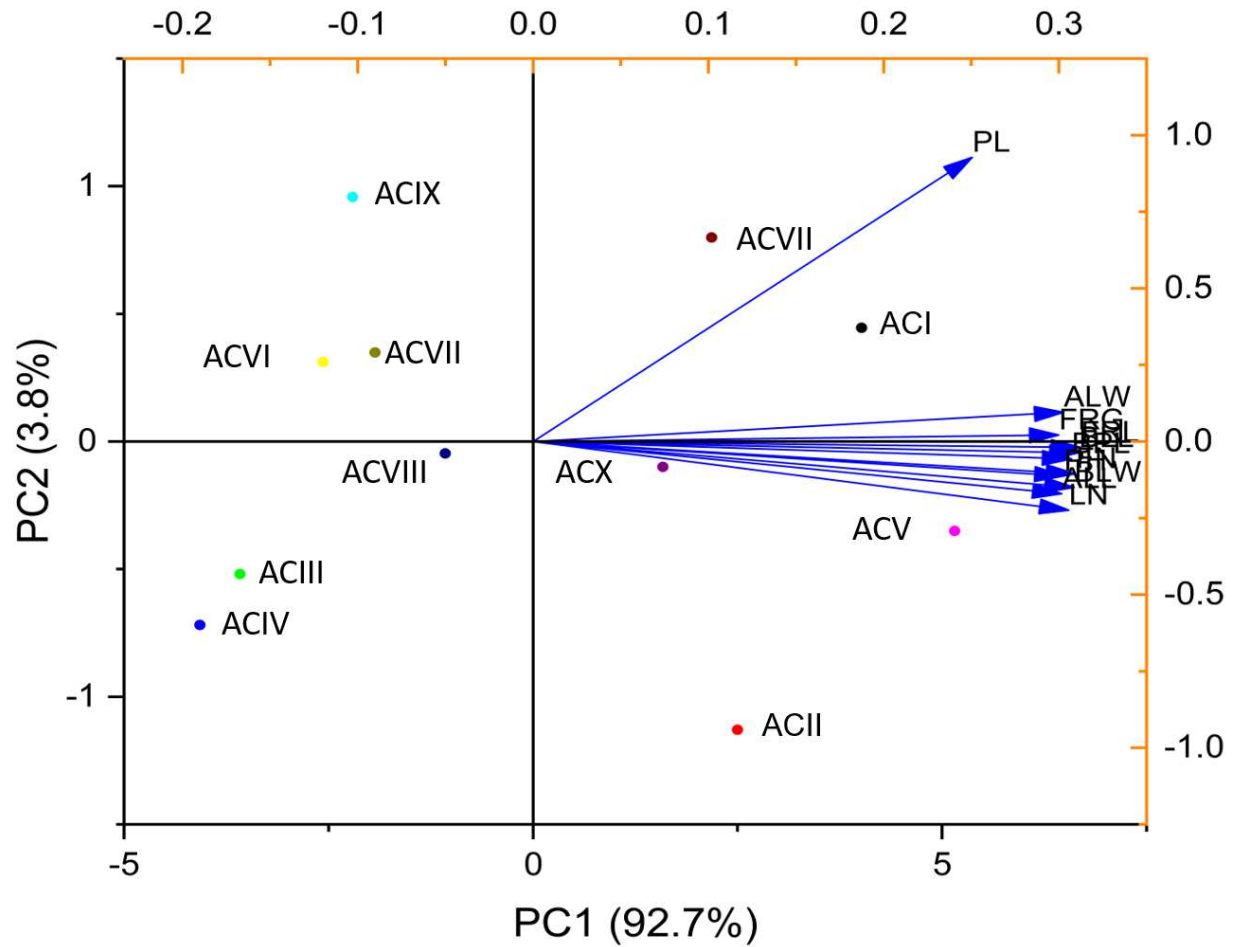


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