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Research article

Distribution modelling and future prediction of a threatened species - *Heracleum candicans* Wall. ex DC.; Within the framework of biotic and abiotic interactions

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ABSTRACT

Heracleum candicans Wall. ex DC. (Hogweed) is under huge anthropogenic pressure in terms of multipurpose collection coupled with climate-driven environmental changes in the region. It was hypothesized that establishment of *H. candicans* with plant associations was due to the complex biotic and abiotic interactions which play a crucial role in its present as well as future distribution. Therefore, we aimed to find out the impact of biotic and abiotic interactions as well as habitat suitability of hogweed, under the current and future climatic scenarios. The association pattern and biotic interactions were evaluated via Cluster Analysis (CA) and Two-Way Cluster Analysis (TWCA). Generalized Linear Model (GLM) and Canonical Correspondance Analysis (CCA) were carried out to assess *H. candicans* in relations to biotic and abiotic variables, simultaneously. Findings showed that abundance of the plant increased with increase in soil pH, EC, OM, N, P, K, sand and silt while decreased with increase in soil erosion and elevation from sea level. *H. candicans* exist in three different plant associations ranging from elevation of 1800–3000 m.a.s.l. For the distribution modelling of the *H. candicans* three machine algorithms such as RF, CART and SVM were used to predict potential habitats suitability, till the end this century. Future distribution of the considered species is primarily influenced by temperature and precipitation seasonality. Ensemble modelling-RF achieved high performance based on AUC-ROC values with training and test data of 1 and 0.979, respectively. The suitable habitat of the plant is expected to show contrasting range changes from 2040 to 2070 under both SSP126 and SSP370 scenarios. By the year 2100, the range of suitable habitat is expected to expand under optimistic, and to shrink in a pessimistic scenarios, SSP126 and SSP370, respectively. The predictive modelling approach could be beneficial for assessing the conservation importance and devising the future management strategies and policies for this and number of other endemic and threatened species, especially the medicinal plants.

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1. Introduction

Heracleum candicans is a perennial herb belonging to the Apiaceae family. It is endemic to the northwestern Hindukush & Himalayas. Floristically, this plant species falls under the Sino-Japanese part of the Hindu-Himalaya region of the Holarctic Kingdom (Yu et al., 2011). The plant is mostly found in the mountains and alpine regions of the north western Pakistan, western India, Northern Afghanistan, Himalayan China, Nepal and Bhutan at altitudinal ranges between 2000 and 4300 m (Jan et al., 2018). Indigenous communities and modern systems of medicine have recognized that each part of the *Heracleum candicans* is used to cure various human ailments (Rawat et al., 2013). Roots of this plant are used by native people as a remedy for skin diseases such as itching and eczema (Gaur, 1999). Shepherds in the Himalayas eat juvenile leaves and shoots and feed to cows to increase milk production (Badola and Butola, 2005).

Hogweed is categorized as vulnerable in the Hindu-Himalayan region (Jan et al., 2018). Despite playing an essential role in ecosystem services, this plant is now facing severe threats due to over collection, exploitation, anthropogenic activities, habitat destruction and climatic changes, but its distribution pattern, ecology and associations have not been investigated in the Hindukush–Himalaya region of the Northern Pakistan. Ruthless collection and exploitation of medicinal plants associated with climate change have disturbed alpine ecosystems, leading to persistent loss of plant diversity and regeneration ability. (Kala and Shrivastava, 2004; Öztürk et al., 2022). The Hindu Kush and Himalayas are recognized by their diverse climatic and topographic variabilities, form rich plant assemblages, high level of endemism and remarkable ecological interactions (Khan et al., 2025; Ahmad et al., 2023). Among these floristic compositions, *Heracleum candicans* play a pivotal role in both ecological services and ethnobotanical practices. (Khan et al., 2013b). In the northwestern Pakistan, high plant diversity and phytogeographic variation have been confirmed by the world's highest mountain systems i-e., Hindukush, Karakoram and Western Himalaya (Manan et al., 2020; Khan et al., 2013). Vegetation studies in these mountains have not yet been fully completed due to their remoteness, inaccessibility, irregular landscapes and constrained geopolitical affairs (Khan et al., 2013b). Most of the botanical studies published in these remote areas are based merely on quantitative data, either for ethnobotany or documentation of their floras or other roles (Ahmad et al., 2021; Signorini et al., 2009). Most Himalayan endemic plant species have not been explored, and small-scale work is underway (Majid et al., 2020); however, little work has been done to quantify plant assemblages across geoclimatic environmental gradients to shed light on the primary factors that influence patterns of local or regional vegetation and biodiversity (Shaheen et al., 2011).

Endemic species are restricted to narrow geographic ranges and have specific habitats at high elevations (Dad, 2019). Various biotic and abiotic variables are involved in the distribution pattern of endemic species in high mountain ranges (Shaheen et al., 2019), and the abundance of these species increases moderately from lower to higher altitudes (Vetaas and Grytnes, 2002). The vegetation of the Himalayas consists of meadowlands of temperate regions and subalpine and alpine grasslands in addition to other landscape types. These ecosystems are rich in endemic species and contribute more to the vegetation of the Western Himalayas. Pakistan host around 400+ endemic species mostly exist in the mountainous parts. The western and northern mountains of Pakistan and Kashmir are composed of 80 % endemic flowering plant species (Ali, 2008). Number of studies have shown that climate change in alpine regions is causing risks for certain species, especially endemics and those of narrow habitats range (He et al., 2019). There are numbers of endemic medicinal plants which are on the verge of endangerment due to overexploitation, and climatic changes (Liu et al., 2025), Hogweed is one of such plants. This plant has been studied extensively for its medicinal values, phytochemicals and perhaps one of the reason for its overexploitation (Chauhan et al., 2014). People rarely care about the conservation, when it comes to the high medicinal and economic value of a species unless the governing bodies interfere or stewrdship is practiced (Teixidor-Toneu et al., 2025). While working on this species we came across with a gap in literature among the ecology, conservation and future prediction of this important endemic medicinal herb.

It is assumed that the patterns of distribution and structure of *Heracleum candicans* and its associated plant species are affected by the stimuli of both biotic and abiotic interactions. Therefore, the present study aimed to 1) identify the distribution pattern of *Heracleum candicans* and its association with other plants under the influence of environmental variables, 2) assess its abundance under the influence of environmental factors, 3) determine various indicators plants which are companion species, and 4) predict habitat suitability under the current and future climatic scenarios using various modelling procedures.

2. Materials and methods

2.1. Study area

A comprehensive field work was conducted in the Hindukush-Himalayas, northern Pakistan. Covering an area of 29,872 Km^2, accounting for 40 % of the Khyber Pakhtunkhwa Province, in the elevation range from 700 m to 7708 m asl (Khan and Ullah, 2016; Khan et al., 2018). The study area consists of massive mountains, rough terrains, medium to steep slopes, hills, plains, undulating valleys and mountains having water tributaries that combine to form major rivers (Hazrat et al., 2008; Khan et al., 2013a) (Fig. 1).

Long-term anthropogenic activities and climatic shifts have been adversely affecting the primary vegetation, water sources and topography of the region over the last 50 years (Ali et al., 2013; Nasrullah et al., 2015). Climatic data from the meteorological stations of Swat, Dir, Chitral and Droash revealed that June with maximum temperature of 34.65 °C, and minimum temperature of 17.62 °C is the hottest month and January with maximum temperature of 9.2 °C and minimum temperature of −2.25 °C is the coldest month of the year in the studied region (Ali et al., 2017). Soil of the study region is primarily sandy loam with an average depth ranging from 0 to 45 cm, and a maximum land slope of 22 % (Nafees et al., 2008). Additionally, in the low lying areas the soil is very fertile and alluvial type that support different types of vegetables, fruit orchards and crops (Ilyas et al., 2015). The annual total precipitation of the study area varies notably for each passing year (ranging from 410 to 1334.3 mm from 2011 to 2013). The average number of weak fronts during the arid season from May to July is 5.13 mm, and that during the rainy season from August to October averages 56.62 mm (Nasrullah et al., 2015). Snowfall often occurs in late November and lasts until mid-March, while relative humidity remains mild throughout the year (Wahab, 2011).

2.2. Sampling biotic variable with special emphasis on plants associated with Heracleum candicans

The quantitative ecological techniques (quadrats along with elevation gradients) were used randomly in each population to record *H. candicans* along with associated plants and soil samples were obtained. Sizes of $10 \times 10\ m^2$, $5 \times 5\ m^2$ and $1 \times 1\ m^2$ quadrat were used for trees, shrubs and herbs, respectively following the standard procedure and long tough journey to find the species by asking people following numbers of authors including (Khan et al., 2022; Khan et al., 2017; Abdullah et al., 2024). Importance value index values (IVIs) for all quadrats were determined from phytosociological data such as density, cover, frequency, relative density, relative cover and relative frequency, using the formulae given before.

$$Desnsity\ (D) = \frac{Total\ number\ of\ individuals\ of\ a\ species\ in\ the\ the\ sampled\ area}{Total\ sampled\ area}$$

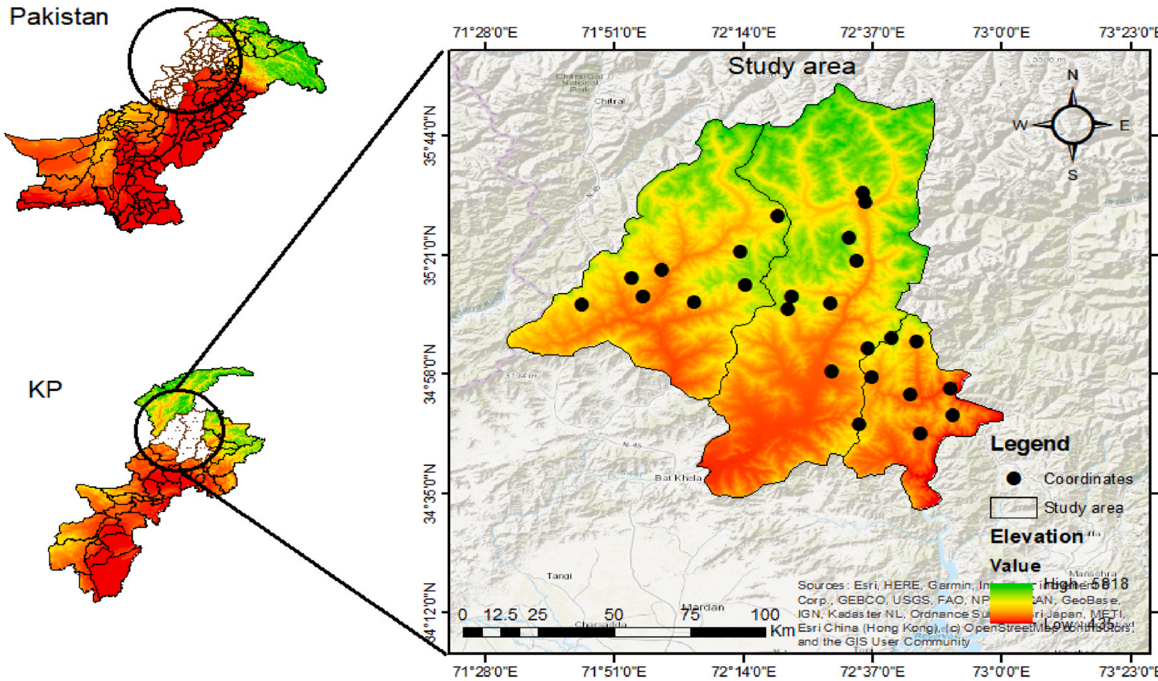

Fig. 1. GIS-generated map of the study area showing 30 sampling stations in the studied region.

$$\textit{Relative density}\ (RD) = \frac{\textit{Density of an individual species in a sampled area}}{\textit{Total densities of all the individuals in sampled area}} \times 100$$

$$\textit{Cover}\left(C\right) = \frac{\textit{Total cover of a species in the sampled unit}}{\textit{Total sampled area}}$$

$$\textit{Relative Cover}\ (RC) = \frac{\textit{Cover of an individual plant species in a sampled unit}}{\textit{Total cover of all the plant species in the sampled area}} \times 100$$

$$\textit{Frequency}\ (F) = \frac{\textit{Number of sampled units in which a species present}}{\textit{Total number of sampled units in the studied area}} \times 100$$

$$\textit{Relative frequency}\ (RF) = \frac{\textit{Frequency of a species}}{\textit{Total frequencies of all the species}} \times 100$$

$$\textit{Importance Value Index}\ (IVI) = \frac{RD + RC + RF}{3}$$

The plant species were collected, tagged, dried, and identified with the help of taxonomists, flora of Pakistan and other relevant literature (Qazi et al., 2023). The collected plant samples, especially the prioritized samples, were correctly labelled, pressed and dried before being mounted on herbarium sheets.

2.3. Sampling the abiotic variables and anthropogenic pressures

A global positioning system (GPS) was used to measure geographic coordinates, i.e., elevation, latitude, and longitude. A digital compass was used to determine the slope aspects, i.e., North (N), South (S), East (E), and West (W). Human and nature-based influences such as overcollection, overexploitation, grazing pressure, habitat destruction, uprooting, climate change impacts, and other anthropogenic pressures were also recorded and properly coded for further analyses (Alam et al., 2023).

2.4. Soil analyses

The soil samples were collected from each population. The topmost layer of soil predominantly consists of humus and organic matter; thus, up to 15 cm of soil was removed, and below the humus layer, the soil was collected from each population. Before physio-chemical analysis, the soil samples were cleaned of pebbles, plant roots, etc., and then kept in polythene bags and properly tagged with their respective codes. A pH meter, electrical conductivity meter, TDS meter, electrical oven, and sieve meshes were used to calculate the pH, EC, TDS, MC, and soil texture (sand, silt, and clay) of each soil sample, respectively. Organic matter (OM), phosphorus (P), nitrogen (N) and potassium (K) levels were analysed in the soil samples at the Agriculture Research Institute of Swat.

2.5. Occurrence of the H. candicans within the framework of biotic and abiotic variables

The survey was conducted during July–October 2022 in order to precisely record the occurrences of *H. candicans*. We recorded 68 occurrence records (Geographic coordinates) of the plant in study area using handheld GPS device (A-GPS).

2.6. Modeling in the scenario of climate change

We have used sdm package in R software to model the distribution of H. candicans. The occurrence locations of the target species were correlated with 19 bioclimatic variables obtained from the WorldClim database (www.worldclim.org) that are known for their relevance in defining species distribution patterns (Hijmans et al., 2005). Multicollinearity among variables was addressed using the Variance Inflation Factor (VIF) method (Cerasoli et al., 2022). The modelling procedure involved ensemble modelling of various Machine learning methods including: Random Forest (RF), Support Vector Machines (SVM), and Classification and Regression Trees (CART) that utilized 1000 background points together with presence records. To maximize computational efficiency, bootstrapping (30 % test data, 3 replicates) and parallel processing were used for validation (Chen et al., 2017). Variable importance analysis revealed predictors' contributions to species distribution, and the models generated current distribution maps.

The ensemble models produced were projected for future climatic scenarios using CMIP6's Shared Socio-economic Pathways (SSPs) data (Anand and Garg) with representative scenarios SSP126 and SSP370 reflecting moderate and high emissions respectively (Adamova and Ukrainskiy, 2023) and for the years 2040, 2070, and 2100. These scenarios offered a framework for evaluating how various climatic paths would affect the distribution of species.

The accurate evaluation of model's predictive performance requires the independent data that were not involved in the training process. Therefore, the species occurrence data was split into two subsets: 75 % for training and 25 % for testing. The models were then evaluated using the Area Under the Curve (AUC) from the Receiver Operating Characteristic (ROC) plot (Phillips et al., 2006). The AUC values range between 0 and 1, reflecting model's ability to distinguish between presence and absence of the species (AUC 1 = perfect discrimination i.e., exceptional performance; 0.8–0.9 is good; 0.7–0.8 is reasonable; 0.6–0.7 is subpar; AUC below 0.5 = model performing worse than random guess (William et al., 2025b). In addition to AUC, the model's performance was also evaluated using the Correlation Coefficient (COR) and True Skill Statistic (TSS). The COR value assess the linear relationship between the predicted and observed data with higher values demonstrating that the model's predictions are consistent with the actual species occurrence data. The TSS, measures the model's overall predictive accuracy by combining sensitivity and specificity. A TSS value close to 1 suggests that the model performs exceptionally well in correctly predicting both presence and absence of the species. Together, these metrics provide a comprehensive evaluation of the model's performance across multiple dimensions (William et al., 2025a).

2.7. Ensemble modeling

Three distinct models were integrated into an ensemble model, weighted by the True Skill Statistic (TSS), to enhance accuracy. The ensemble raster representing the suitability of habitat (0 = unsuitable-1 = very high suitability) was reclassified into five classes with equal interval representing Unsuitable (0–0.2), Low suitability (0.2–0.4), Moderate (0.4–0.6), High (0.6–0.8) and very high (0.8–1) suitability classes.

2.8. Statistical analyses

Species Area Curve (SAC) was generated via PCORD software to determine the exploration of plant species along with the addition of sampling sites and to understand the adequacy of sampling. PCORD (version 5) software was used to group different plant species and populations/sites into inherent plant associations on the basis of their shared characteristics and differences. (Khan et al., 2017). Canonical correspondence analysis (CCA) indicator species and generalized linear modelling (GLM) were carried out through CANOCO (version 4.5) software to examine the relationships between vegetation and biotic and abiotic variables (Khan et al., 2017). Species Distribution modelling (SDM) was carried out in R software along with GIS to predict habitat suitability of the species under the current and future climatic scenarios (Paul et al., 2023).

3. Results

A total of 72 associated plant species/biotic components in the vicinities of *H. candicans* were recorded in the studied area. These species belong to 34 families, including 6 trees (8 %), 10 shrubs (14 %) and 55 herbs (78 %). Species area curve analysis showed the adequacy of the sampling in the study area. Two Way Cluster Analysis divided the plant species and sampling units in 3 associations/habitat types. Indicator Species Analysis (ISA) was used to identify the indicators/companions of these communities. The final emsemble modelling results showed that Random forest (RF) model is fit to demonstrate generalization and predictive accuracy with highest values of 1 for training and 0.979 for test data, as compare to the explanation of both (CART) and (SVM).

3.1. Species area curve (SAC)

A Species Area Curve (SAC) was generated using PCORD Software to determine the increasing number of listed species along the increasing number of sampling sites. Taking the population data integrated with Sørensen distance values, was generated for 72 plant species listed in 30 populations. The SAC indicated that the new species were exploring up to sampling point 50, and after site 28, the curves became straight. The leveled off curve, indicate that sampling units laid down in the desired area were sufficient (Fig. A.1).

3.2. Cluster analysis (CA)

Cluster analysis was carried out via PCORD (version 5). The plant species along the abiotic gradients and 30 sampling points were divided into 3 plant associations under the impact of different reasonable abiotic factors (Fig. A.2).

3.3. Two-way cluster analysis (TWCA)

Two-way cluster analysis was employed to determine the distribution of species in each population along with *H. candicans*. The white dots indicate absence, whereas the black dots represent the presence of plant species in each population of each zone (Fig. A.3). In the graph, several clusters are structured such that the species are assembled with their corresponding associated species. Thes analyses also showed that *H. candicans* found in company with other plant species such as *Juniferus communis*, *geranium wallichianum*, *sibalia procumbens*, *Rosa webbiana*, *Bistorta amplexicaulis* and *Trifolium pratense*. *J. communis* is unedibale for any grazing animal thus provide shade for the *Heracleum candicans*. *Rosa webinna* is spiny in nature and *Heracleum candicans* protect itself from grazing and other anthropogenic pressures via living in association with *R. webianna and Juniperus communis* and hide itself in spiny bushes of *Rosa* or thickly branched shade of *Juniper*. Additionally, the taxon of these associated plants are not the members f *H. candicans*, family i.e., Apiaceae (Umbelliferae) indicating the plants non competitive nature for the abiotic resources (Fig. A.3).

3.4. Response towards various environmental gradients

The Generalized Linear Model (GLM) showed the response of species to various abiotic variables. The abundance of *Heracleum candicans* increased with the increase in both pH and EC. The abundance of the plant also increased with increasing total dissolved solids (TDS) to some extent, and then started to decrease as shown in (Fig. A.4). The organic matter (OM), potassium (K), nitrogen (N), phosphorus (P) and sand contents were positively correlated with the abundance of the species, as these variables increased the abundance also increased. In comparison with other variables such as, moisture content (MC) and silt, they showed peculiar types of responses. At low moisture and silt, the abundance of the plant remained high, but gradually, the abundance increased with increasing contents of both parameters. Soil erosion negatively impacts the abundance of plants. Increases in clay and anthropogenic pressure also negatively impacted the abundance of *H. candicans* in the study area.

3.5. Plant associations/assemblages and biotic interactions

A total of three plant associations were identified through TWCA using PCORD (version 5). A comprehensive overview of these associations, including associated plant species and relevant abiotic factors, is given below.

3.5.1. *Quercus semicarpifolia-Indigofera heterantha-Viola canescens* association

Heracleum candicans along with associated plants clustered into 7 populations in the study area. The elevation range for this association varies from 1800 to 2500 m asl. It is a moist temperate vegetation association dominated by tree species. The top indicator plant species of this association are *Quercus semicarpifolia* (P* = 0.0212), *Indigfera heterantha* (P* = 0.0006) and *Viola canescens* (P* = 0.0462), which are trees, shrubs and herbs, respectively (Table 1). The top abiotic variables contributing to the formation of this association were low phosphorus contents (5–9 %), low nitrogen (0.021–0.601 %), low Electrical Conductivity (1.5–190.7 μS), low moisture content (2–6 %), and low organic matter (1.2–4.9 %). Other abiotic variables that contributed slightly were high total dissolved solids (11–243 ppm) and low pH (4.1–6.71) (Fig. A.5).

3.5.2. *Zanthoxylum armatum-Cotoneaster microphyllus-Artemisia vulgare* association

A total of 6 out of 30 populations are clustered on the basis of the Sorenson similarity index in this plant association. The association is found in the total range of 2000–2500 m asl. The association commonly consists of moist temperate vegetation. The top indicator species of this association were *Zanthoxylum armatum* (P* = 0.0212), *Cotoneaster microphyllus* (P* = 0.0038) and *Artemisia vulgare* (P* = 0.0002) (Table 1). The important abiotic factors involved in the formation of this association are high silt (3–55 %), low phosphorus (5–9 %) and low nitrogen (0.02–0.601 %), whereas moderate pH (4.1–6.71) and high TDS i-e., 11 ppm (Fig. A.6) also contribute a small amount to the establishment of this association.

3.5.3. *Diospyros lotus*–*Juniperus communis*–*Hylotelephium ewersii* association

This association was relatively common in the high altitudinal range (2200–3000 m asl) in the study area. The association existed in 17 out of 30 populations. The association is mostly composed of dry temperate vegetation and is dominated by tree species. The prime indicator species of this association are *Diospyros lotus* (P* = 0.0506), *Juniferus communis* (P* = 0.037) and *Hylotelephium ewersii* (P* = 0.0448), a layer of tree, shrub and herb, respectively (Table 1). The major abiotic variables contributing to the formation of this association are organic matter low (1.2–4.90 %), high clay (1–18 %) and moderate humidity (1–3) (Fig. A.7). Anthropogenic pressure (overcollection of medicinal plants), grazing pressure and soil erosion were observed to be great threats to this association.

Table 1
Comprehensive overview of the leading indicator/companion species within each association, under the influence of abiotic variables; organic matter, Total dissolved solids, Phosphorus, Nitrogen, Silt and pH.

S. No	Indicator Species	Variables	IV	*P** value
Diospyros *lotus- Juniperus communis- Hylotelephium ewersii* Association				
1.	*Diospyros lotus* L.	Organic matter	33.3	0.0506
2.	*Juniperus communis* L.	Organic matter	60.6	0.037
3.	*Hylotelephium ewersii* (Ledeb.) H. Ohba	Humidity	75	0.0448
***Quercus semecarpifolia -Indigofera heterantha-Viola canescens* Association**				
1.	*Quercus semecarpifolia* Sm.	TDS	42.9	0.0212
2.	*Indigofera heterantha* Wall. ex Brandis	Phosphorous	83.3	0.0006
3.	*Viola canescens* Wall.	Nitrogen	33.3	0.0462
***Zanthoxylum armatum - Cotoneaster microphyllus-* Artemisia vulgare Association**				
1.	*Zanthoxylum armatum* DC.	Silt	42.9	0.0212
2.	*Cotoneaster microphyllus Wall. ex Lindl.*	TDS	59.8	0.0038
3.	*Artemisia vulgare* L.	pH	100	0.0002

3.6. Canonical correspondence analysis (CCA) showing the distributions of species under the iabiotic interactions

All the abiotic variables such as EC, pH, TDS, organic matter, nitrogen, potassium, phosphorus, humidity, moisture content, altitude, sand, silt and clay particles influenced the distribution, abundance and evenness of recorded species in the study region (Fig. A.8). The arrows show the dimensions among various variables and the extent of the relationships among them. Abiotic variables occurring in the same axes indicate positive correlations, whereas the parameters occupying the opposite direction show negative correlations. In the first quadrant of the CCA biplot, moisture content, organic matter, sand, potassium and humidity influenced the distribution of species such as *Anaphalis margaritacea, Arisaema jacquemontii, Bupleurum falcatum, Carex infuscata, Corydalis diphylla, Cotoneaster microphyllus, Heracleum candicans,* etc. In the second quadrant, species such as *Bergenia ciliata, Cyperus rotundus, Eragrostis cilianensis, Erioscirpus comosus, Hedera nepalensis, and Pilea umbrosa* are associated with pH, phosphorus and altitude. Species such as *Aconitum rotundifolium, Aster molliusculus, Bergenia ciliata, Bistorta amplexicaulis, Geranium wallichianum, and Hylotelephium ewersii* are gathered with clay particles in the third quadrant. In the last quadrant of the CCA biplot, nitrogen, TDS, EC and silt influenced the distributions of *Aristida cyanantha, Cynodon dactylon, Cynoglossum lanceolatum, Diospyros lotus, Fragaria nubicola, Indigofera heterantha, Morus alba,* etc.

3.7. Evaluation of predictive models through AUC-ROC curves

Our findings showed that the performance of each model varies a bit for instance, Random Forest (RF) model signifies excellent generalization and predictive accuracy with highest values of 1 for training and 0.979 for test data. The Area Under Curve (AUC) values for training is 0.973 and for test data is 0.965 in Support Vector Machine (SVM) model ensured very significant results regarding the model predictive accuracy and generalization. The Classification and Regression Trees (CART) model also showed good performance regarding model generalization and accuracy with AUC values of 0.954 and 0.85 for training and test data respectively. The slight downfall in the values indicated little weaker execution in comparison with RF and SVM (Fig. 2).

3.8. Contributions of variables

Highly uncorrelated variables for the accuracy of model development were selected. After this analysis, six relatively important variables were retained for predicting the model outcomes which includes, bio02 (Mean Diurnal Range), bio04 (Temperature Seasonality), bio08 (Mean Temperature of Wettest Quarter), bio09 (Mean Temperature of Driest Quarter), bio15 (Precipitation Seasonality), bio17 (Precipitation of Driest Quarter). The bar plot shows bio04, bio15 and bio17 are highly important according to their contributions (Fig. 3). Due to the pivotal role of in model accuracy, these variables display significant ecological and climatic factors that mould species distribution.

3.9. Habitat suitability of the plant under different climatic scenarios

Under the current climatic conditions *Heracleum candicans* is distributed in northwestern and southeastern parts of the study area. The unsuitable habitat is (10,082 km^2), low (1102 km^2), moderate (936 km^2), high (855 km^2), while the very high suitable habitat is (270 km^2) for this species (Fig. 4 A) (Table 3). By the year 2040, the population is expected to expand towards western and northern parts covering (1037 km^2) area of very high suitable habitat under both the optimistic and pessimistic scenarios (SSP 126 and SSP 370) (Fig. 4B and C). The population is expected to highly shrink, occurring in (75 km^2) area under the scenario (SSP 126) and expected to expand towards northern, western and eastern parts under the scenario (SSP 370) by the year 2070 (Fig. 4D and E). By the year 2100, the population of the plant is

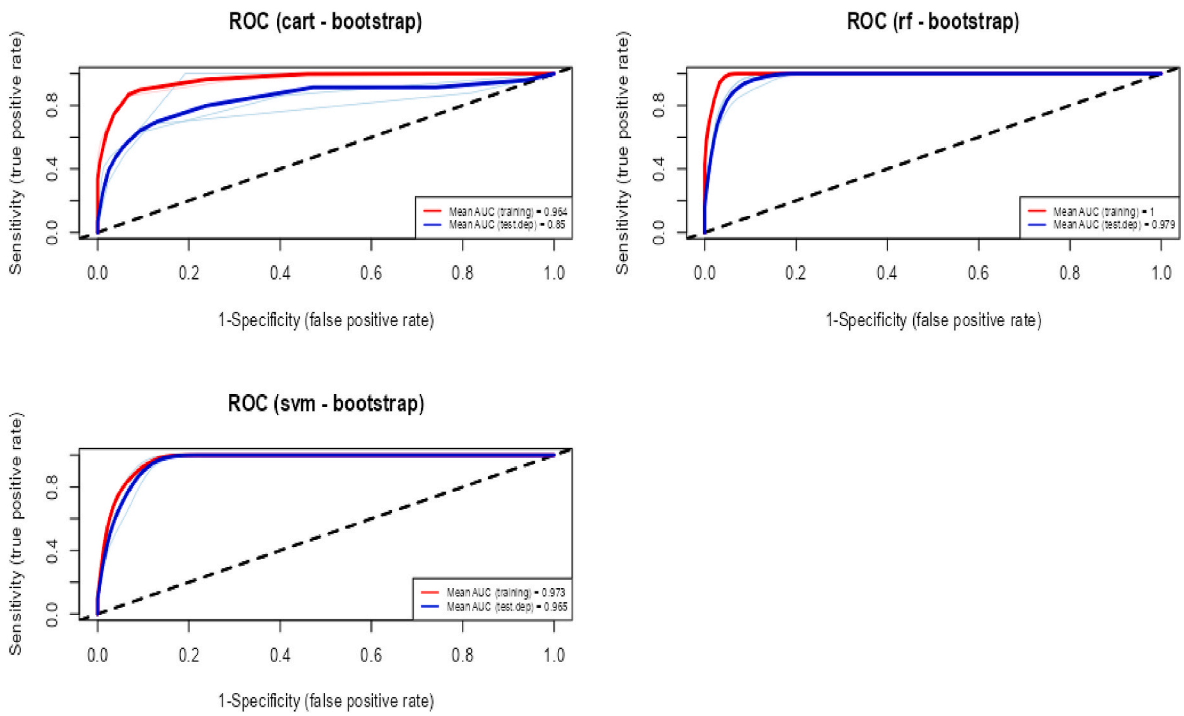

Fig. 2. Machine learning algorithms such as random forest, classification and regression trees and support vector machine.

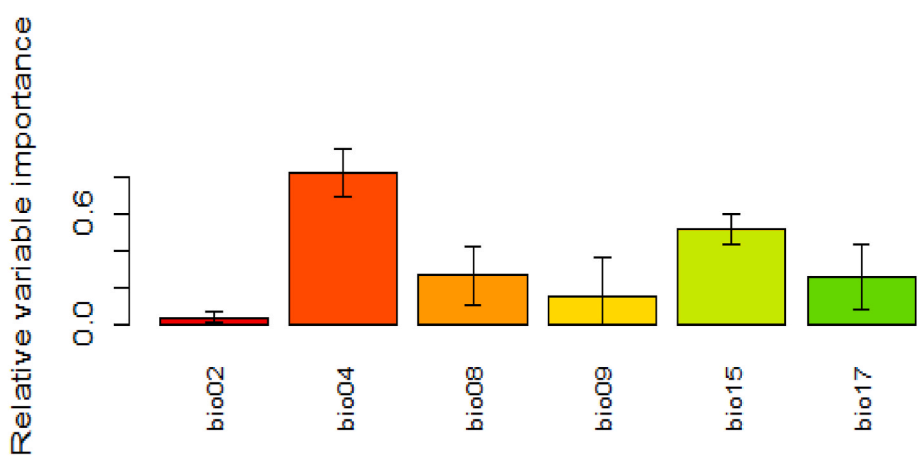

Fig. 3. Contribution of important variables for distribution of *H. candicans.*

predicted to shrink and move towards eastern parts, covering (439 km^2) area under the optimitic scenario (SSP 126) and expected to highly shrink towards northeastern parts under the pessimisted scenario (SSP 370) (Fig. 4F and G) (Table 3).

4. Discussion

H. candicans is commonly present in the Northwest and Trans Himalayan zones (Kaul, 1989). This endemic Himalayan species is also found in the montane alpine regions of western Pakistan and southwestern China (Butola and Badola, 2007). It face numerous challenges like over collection, anthropogenic pressures and continuous climatic change driven habitat degradation. The present study was conducted to predict habitat suitability under the current and future climatic scenarios through distribution modelling of *Heracleum candicans* Walls. in relation to its companion plants and abiotic drivers in the western Himalayas. The species was mostly found on the rocky slopes and open areas, in varying plant associations. It prefer to grows on open slopes, riverbeds, meadows, rocks and dry places covered by humus. Phytogeographically, the plant is restricted to Sino-Japanese region, which is part of the Holoarctic kingdom (Khan et al., 2014; Yu et al., 2011).

H. candicans a vulnerable endemic species exist in various associations of plants in the Himalayas under the influence of various living and nonlivinng factors. For instance, it grows in the vicinity of companions such as *Juniferus communis* and *Rosa webbiana* as per our field observations. These plants play a crucial in the existence and flourishment of *H. candicans*, as the needles leaves of *J. communis* and spiny nature of *R. webbiana* protect this plant from grazing animals and multi purpose anthropogenic activities. Such biotic interactions always play crucial roles in the survival of plants with narrow ecological amplitudes (Khan et al., 2013b). It also found in association with other plants i.e., *Quercus semicarpifolia*, *Indigofera heterantha* and *Viola canescens*. Other rare indictor plants were also found in these associations under the influence of various environmental variables (Table 2). The concept of indicator and rare indicator plants is a vast discussed topic and can be seen in dozens of studies include those of Himalayas (Khan et al., 2016; Ullah

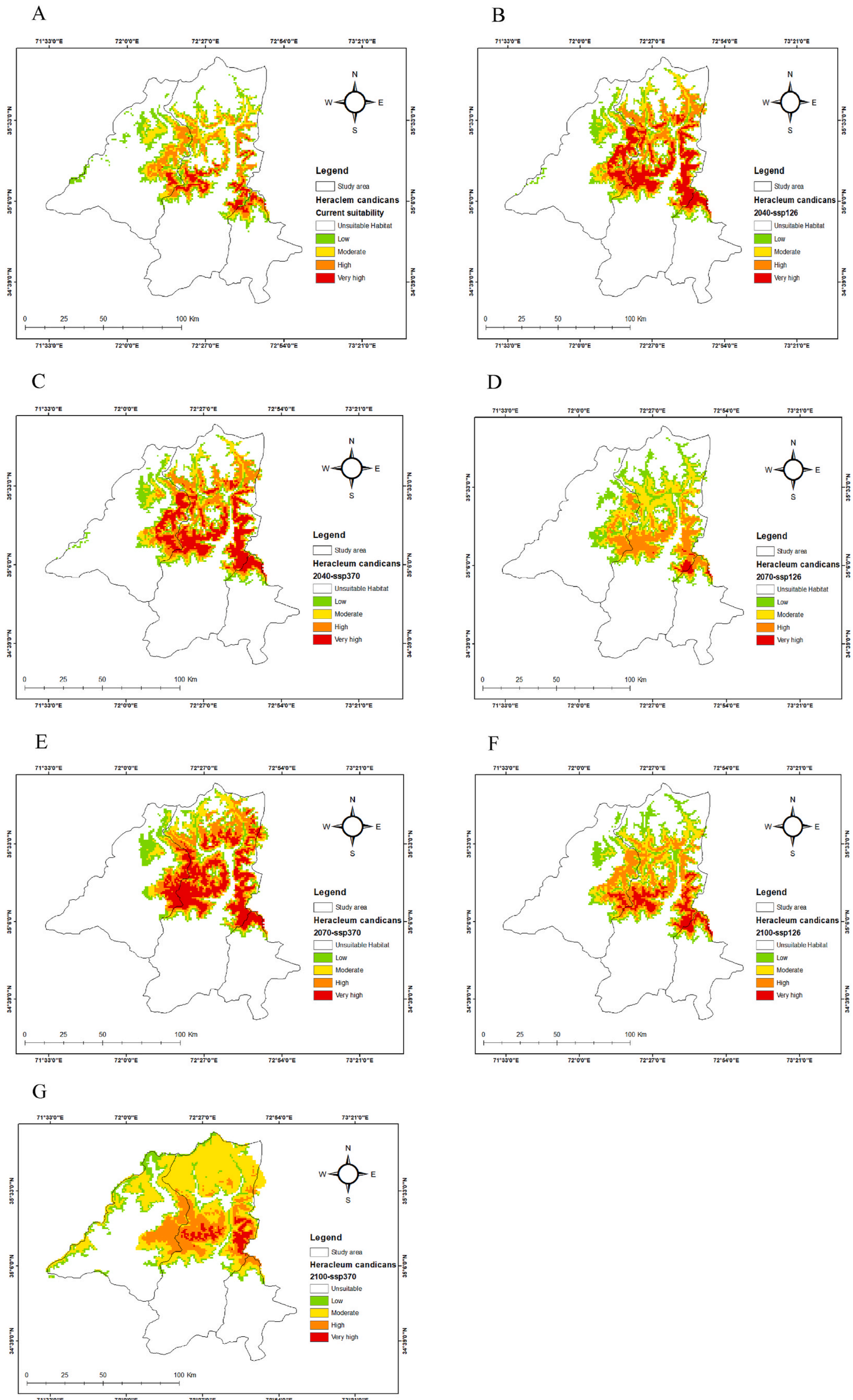

Fig. 4. Maps showing the suitable habitats under current and future climatic scenrios**.** The white color shows unsuitable habitat, green shows low suitable, yellow shows moderately suitable, orange shows high and red shows very high suitable habitats for the species.

Table 2
Rare indicator species under the influence of abiotic variables in the study area.

S. No	Plant species	Element	Mxgrp	IV	P value
1.	*Adiantum* sp	EC	0	50	0.0242
2.	*Arisaema jacquemontii* Blume	P	9	50	0.0288
3.	*Artemisia vulgaris* L.	pH	0	100	0.0002
		N	1	85.7	0.0476
4.	*Aster molliusculus* (Wall. ex Lindl.) C.B.Cl.	OM	3	62.5	0.0018
5.	*Berberis lycium* Royle	Aspect	0	33.3	0.0482
6.	*Bistorta amplexicaulis* (D.Don) Greene	Clay	5	25.5	0.012
7.	*Bupleurum falcatum* L.	Aspect	2	42.9	0.0212
8.	*Cannabis sativa* L.	Humidity	0	66.7	0.001
9.	*Cotoneaster microphyllus* Wall. ex Lindl.	TDS	0	59.8	0.0038
10.	*Diospyros lotus* L.	OM	6	33.3	0.0506
		Aspect	0	33.3	0.0456
11.	*Dryopteris* sp	EC	0	38.9	0.0578
12.	*Erigeron bonariensis* L.	N	1	88.9	0.031
		Humidity	0	83.3	0.0006
13.	*Erioscirpus comosus* (Wall.) Palla	N	1	88.9	0.0292
		Clay	4	63.2	0.0208
14.	*Fragaria nubicola* Lindl. ex Lacaita	Aspect	0	43.3	0.02
15.	*Galium asperuloides* Edgew.	Aspect	0	33.3	0.0486
16.	*Geranium wallichianum* D.Don	MC	4	63	0.0016
17.	*Hedera nepalensis* K.Koch	pH	6	33.3	0.0474
18.	*Hylotelephium ewersii* (Ledeb.) H.Ohba	Humidity	8	57.7	0.0284
19.	*Impatiens brachycentra* Kar. & Kir.	Sand	6	50	0.0218
20.	*Indigofera heterantha* Wall. ex Brandis	TDS	0	83.3	0.0006
		N	1	88.9	0.031
21.	*Isodon rugosus* (Wall.) Codd	N	1	88.9	0.0328
		Aspect	0	83.3	0.0002
22.	*Juniperus communis* L.	OM	2	60.6	0.037
		Aspect	1	44.1	0.0516
23.	*Oxalis corniculate* L.	TDS	0	83.3	0.0006
		N	1	88.9	0.031
24.	*Plantago lanceolata* L.	Aspect	0	33.3	0.0486
25.	*Quercus semecarpifolia* Sm.	P	2	42.9	0.0212
26.	*Ranunculus repens* L.	Aspect	0	38.2	0.0594
27.	*Rhodiola quadrifida* Fisch. & C. A.Mey.	MC	3	59.3	0.0324
		Altitude	36	53.3	0.047
28.	*Rosa webbiana* Wall. ex Royle	MC	5	42.9	0.0522
		Clay	10	75	0.0426
29.	*Saussurea albescens* (DC.) Sch. Bip.	P	2	42.9	0.0212
30.	*Senecio chrysanthemoides* DC.	Sand	6	40.9	0.0402
31.	*Seteria virdis*	N	1	88.9	0.0306
		Aspect	0	59.8	0.0046
32.	*Sibbaldia procumbens* L.	P	2	47.4	0.0444
33.	*Sorghum halepense*	Aspect	0	83.3	0.0004
34.	*Strobilanthes urticifolia* Wall. ex Kuntze	pH	6	45.2	0.0334
		N	1	92.3	0.02
		Aspect	0	66.7	0.0014
35.	*Thalictrum cultratum* Wall.	OM	1	40	0.0548
36.	*Trifolium pratense* L.	Aspect	2	61.9	0.001
37.	*Urtica dioica* L.	N	1	96	0.0078
		Aspect	0	50	0.01
38.	*Valeriana jatamansi* jones	pH	6	45.2	0.0316
		Aspect	0	43.3	0.0228
39.	*Viola canescens* Wall.	pH	6	33.3	0.051
		N	0	33.3	0.0462
40.	*Zanthoxylum armatum* DC.	Silt	2	42.9	0.0212

et al., 2022). Number of studies at alpine zones reveal abundance of a few leading taxa, such as *Sibbaldia cuneata, Poa pratensis, Poa alpina* and *Carex nubigena*, that attributed to their narrow ecological amplitude and enhanced adaptation to the short growing season (Dad, 2019). Alpine ecosystems of Himalayas show relatively, rich floral diversity, with prevalent distributions and dominance resulting from species' morphological, physiological, and genetic adjustments to the area's varying microclimatic conditions (He et al., 2019). Land use/land cover

Table 3
The area covered by the plant in various predictive years. Class 1, 2, 3, 4 and 5 indicating the unsuitable, low, moderate, high and very high suitable habitats, respectively.

Years	Scenarios	Class 1	Class 2	Class 3	Class 4	Class 5
Current		10,082 Km^2	1102 Km^2	936 Km^2	855 Km^2	270 Km^2
2040	126	9296 Km^2	970 Km^2	869 Km^2	1073 Km^2	1037 Km^2
	370	9296 Km^2	970 Km^2	869 Km^2	1073 Km^2	1037 Km^2
2070	126	9812 Km^2	1202 Km^2	1193 Km^2	963 Km^2	75 Km^2
	370	8975 Km^2	962 Km^2	877 Km^2	1135 Km^2	1296 Km^2
2100	126	9485 Km^2	1140 Km^2	1009 Km^2	1172 Km^2	439 Km^2
	370	13,245 Km^2	0	0	0	0

in the Himalayas, is generally affected by human activities like grazing, multi-purpose collection, agriculture extension and natural drivers for instance; sliding, glaciation and increase in temperature. These fragile ecosystem are under the huge risk of fragmentation, drought and soil erosion.

Diverse biotic and abiotic variables that constitute a suitable habitat are the primary factors responsible for existence of this endemic plant, overall high endemism in the Himalayan montane ecosystems and constitution of unique plant associations (Khan et al., 2013c). Climatic conditions at high elevations remain harsh, but this and companion plant species show resilience, due to their adaptation, and hence they are able to use accessible resources, effectively (Dad, 2019). Moreover, abiotic variables such as high TDS (11 ppm), and low phosphorus contents (5–9 %), low nitrogen (0.02–0.601 %), low electrical conductivity (1.5–190.7 μS), low moisture content (2–6 %), and low organic matter (1.2–4.91 %) are the determining factors for the abundance of indicator associated plants of *H. candicans*. The direct correlations between quantitative characteristics of biodiversity and soil physio-chemical properties have also been documented by numbers of other authors including but not limited to (Canfora et al., 2017; Liu et al., 2022). Results of the CCA analyses revealed important interactions between biotic and abiotic components i.e., TDS, EC, pH, MC, OM, N, K, P, humidity, altitude, sand, silt and clay particles. The CCA biplot indicates that TDS, EC, organic matter, nitrogen, pH, silt and clay significantly affect species distribution in the study area. These results are consistent with the findings of (Ullah et al., 2022), who studied the Yakhtangi Hill of the Hindu-Himalaya range, Northwestern Pakistan. Results of the edaphic factors led to the conclusion that topography and soil properties are both involved significantly, in the variation of species and abundance (Bennie et al., 2008; Ullah et al., 2022).

In current study we also checked the individual and combined impact of some abiotic drivers such as soil physio-chemical properties and bioclimatic variables as indicators to monitor the effects on species distribution and its habitat degradation. Generalized linear model analyses, by putting the *H. candicans* population and abundance data along with abiotic data, revealed that the species abundance and diversity of the companion species decreased along the increasing elevation. The decline in species diversity along altitudinal gradients is a well-recognized ecological pattern, primarily driven by the challenging climatic conditions in the alpine zones; especially, downfall in the temperature (Bonn et al., 2002; Boscutti et al., 2018). Abundance of *H. candicans* also decreased with decreasing TDS, increasing soil erosion and clay particles, whereas the abundance increased with increasing other parameters, such as pH, EC, organic matter, nitrogen, potassium, phosphorus, sand and silt particles (Fig. A.4). Climatic changes bring a continuous rise in temperature, that in turn push the altitudinal limits of such species upward. The existing habitats of *Heracleum* on the mountains having steep slopes, are on the verge of land degredation due to climate driven anthropocene. The influences of environmental parameters on species abundance and scarcity have been investigated, richly by researchers in all sorts of ecosystem around the globe (Ahmad et al., 2025; Ullah et al., 2022).

Climate change is one of the emerging challlanges in the current century that damage species habiats, especially, in high elevated mountain ecosystems, because of the rising temperature, melting snow, erosion, and uneven precipitation. Researchers have adopted number of methods such as Species Distribution Modelling (SDM), MaxEnt Modelling and others to predict the effects of climate change on such ecosystems and the species exist there. These procedures help to record the impacts of changing climate on valuable and sensitive species for better management and conservation (Khan et al., 2022). In SDM analyses different predictive models are used to forecast the current and future potential habitats of the species. In our case, we used machine learning algorithms such as RF, CART and SVM as predictive models for the habitat suitability of the species. Based on the AUC-ROC curves, Random forest (RF) model signifying excellent generalization and predictive accuracy with highest values of 1 for training and 0.979 for test data as compare to the results of CART and SVM. Many researchers have also widely used these predictive models and methology for the accurate distribution of plant species (such as *Astragalus gossypinus, Bromus tomentellu and Festuca govina*) (Sharifipour et al., 2023). Other researchers used MaxEnt model to predict potential habitat, suitable for threatened medicinal plants in the Himalayas (Arghadyuti Banerjee et al., 2017). In our case, for the predictive model RF; the AUC value was (0.98), COR value (0.73) and TSS value (0.91), showed superior model performance, as it is also conveyed for other species by (Gao et al., 2021). We have used ensemble model rather than MaxEnt due to the rare availability of our targeted species though it has relatively more limitations. Nevertheless, we suggest Random Forest Predictive model among our three different used models for the rarely distributed endemic species of the fragile ecosystem. Moreover, we have used merely 19 bioclimatic variables obtained from worldclim data base for the distribution modelling of the considered species, but not used other abiotic factors for instance soil chemical and physical properties, and soil nutrients. In our case, out of the 19 bioclimatic variables used for the current and future predictions Temperature Seasonality, Precipitation Seasonality and Precipitation of Driest Quarter are recognized as important variables for distribution of considered plant species in the study area. Many researchers (Majeed et al., 2021) also revealed the significant role of topographic factors, precipitation, temperature which influenced the distribution of plant species particularly in the mountainous regions in Asia. Predictions under future climatic scenarios (SSP126 and SSP370) showed absolute decline in potential suitable habitat of the species for current to 2040, 2070 and 2100, as advocated by many other researchers for different species in different years (Priatna et al., 2025; Distler et al., 2015).

Anthropogenic and climatic pressures cause destruction of the *Heracleum candicans'* population as well as its habitat degradation. Therefore, we recommend suitable modelling, regular monitoring, sustainable utilization, habitat conservation and proper policies for the species like *H. candicans*, and other in mountain systems of the world in general and Himalayas in particular. Systematic grazing from two to three years can help to sustainably utilize or increase the population of such species (Ahmad et al., 2025; Khan et al., 2013). Additionally, *in-situ* and *ex-situ* conservation strategies and community participatory approaches could be implemented properly to conserve the species in their native habitats.

5. Conclusion

The current findings concluded that the Hogweed - a medicinally important plant with endemic nature on the faceof serious climate change challenges, overcollection and habitat destruction need an immediate conservation attention. Having had the evidence on the impact of biotic and abiotic variables on the distribution of this, and associated plants, the conservation manager and policy makers can have an ease to devise work plan for this plant. Using robust statistical tools like classification via CA & TWCA, ordination tools and Machine learning algorithms such as RF, CART and SVM map and predict the potential suitable habitats for species in the years 2040, 2070 and 2100 under different climatic scenarios. Our findings revealed that, under the optimistic SSP126 and pessimistic SSP370 scenarios, the potential suitable habitat for the targeted species is expected to be declined, remarkably, by the end of this century. In summary, *H.candicans*, is diminishing at an alarming rate due to frequent collection for trade, medicinal uses and grazing. Therefore, conservation strategies, sustainable use and habitat safety and proper policy implementations are needed to safeguard this endemic species in the Hindu-Kush Himalayas in general and studied area in particular.

CRediT authorship contribution statement

Jawad Hussain: Writing – original draft. **Shujaul Mulk Khan:** Supervision. **Muhammad Shakeel Khan:** Methodology. **Zafeer Saqib:** Formal analysis. **Abdullah:** Formal analysis. **Zeeshan Ahmad:** Data curation. **Maria Shah:** Visualization. **Nazir Mohammad:** Methodology. **Zareena Batool:** Methodology. **Amir Sohail:** Methodology. **Jie Liu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing Interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125818.

Data availability

The data that has been used is confidential.

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