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Original research article

Ecological dynamics, ethnobotanical significance, and habitat projections for *Arisaema costatum* (Wall.) Mart. in response to climate change in Nepal

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ABSTRACT

The unique landscape of Nepal supports diverse ecological niches that are home to valuable plants, benefiting various ethnic groups. Wild edible plants have been essential for the livelihoods of indigenous peoples and local communities due to their affordability, ease of harvest, and renewable nature. However, climate change is altering the habitat, distribution, ecology, and phenology of plant species in the Himalayas. One such important species in Nepal is *Arisaema costatum*, which has multiple indigenous uses. Unfortunately, climate change, deforestation and land use changes have led to continuous changes in the distribution and habitats of *A. costatum*. We conducted field research involving 280 quadrats (2 ×2 m) and 210 interviews. By utilizing MaxEnt modeling and considering different climate change scenarios (Shared Socioeconomic Pathways 4.5 and 8.5) as well as climatic predictors and species localities, we analyzed 196 geospatial data points. This allowed us to evaluate the present suitable environment and predict potential habitats in 2050 and 2070. Our findings revealed that *A. costatum* is used as a vegetable by indigenous and local communities in the Nepal Himalayas. Traditional fermentation and detoxification techniques are employed for its preparation. The plant plays a vital role in household food and nutrition, income generation, and health security. Elevation, annual mean temperature (BIO-1), and precipitation during the warmest and coldest quarters (BIO-18 and BIO-19) were identified as the most influential factors for projecting the future distribution of *A. costatum* in the Nepal Himalayas. Approximately 14% (21121.75 km^2) of Nepal's land was found to be suitable habitat for this species, with the Gandaki, Bagmati, and Koshi provinces in the temperate regions particularly well-suited compared to other provinces. Highly suitable areas are expected to gradually decrease from 0.14% in 2050 and 1.65% in 2070. Thus, the anticipated loss of *A. costatum* habitats and the increasing temperatures due to climate change in the Nepal Himalayas, urgent integrated research and development programs are necessary to address this issue.

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1. Introduction

The unique landscape of Nepal has established many ecological niches that harbor high-value plants (Subedi, 2006; Rana et al., 2015; Thapa et al., 2021), and several ethnic groups have adopted them (Manzardo, 1977; Ghimire, 2008; Shoaib et al., 2021). High-value plants of this region have been a traditional source of food, medicine, and income for people living in remote and rugged mountain regions of Nepal Himalaya (Lama et al., 2001; Bhattarai et al., 2009; Uprety et al., 2012; Ambu et al., 2020; Awasthi et al., 2023). Conservation and management of high-value plants are crucial because they provide opportunities to generate local and national capital (Olsen and Helles, 1997; Rajbhandary and Ranjitkar, 2006; Rana et al., 2017). At the same time, anthropogenic pressures in Nepal Himalaya, annoying by geopolitical tensions, has threatened many existing high-value plants and will be in future too (Shrestha and Bawa, 2014; Rana et al., 2015; Acharya et al., 2022). Overharvesting of high-value plants alter the spatiotemporal patterns of the Himalaya.

In addition to anthropogenic pressure, climate change creates adverse effects in the ecological diversity of high-value plants. The global surface temperature increased by the end of the 21st century is likely to exceed 2.0 °C across many scenarios Intergovernmental Panel on Climate Change (IPCC). Nepal is projected to experience significant increases in mean annual temperature, with a rise of 1.4 °C by 2030, 2.8 °C by 2060, and 4.7 °C by 2090, Nepal Climate Vulnerability Study Team (NCVST, 2009). According to Ministry of Science, Technology and Environment (MoSTE, 2014), the country is also expected to witness an increase in total precipitation by 6% and 12% within 2050 and 2080, respectively. The ecosystem, distribution and habitat of valuable plants are directly affected by rising temperature. Distribution of plant species is shifting in their specific geographic ranges in response to changes in bioclimatic variables (temperature and precipitation) (Elith and Leathwick, 2009; Lenoir and Svenning, 2015; Rana et al., 2020; Shrestha et al., 2021). The species range shift is seen either at the species level or at ecosystem level which directly affects the species composition, structure and phenology (Van der Putten et al., 2010; Rana et al., 2017). Therefore, climate change and its impact must be considered while preparing for valuable plants conservation planning. Species distribution and its ecological characteristics must be taken in to consideration as a part of the conservation and management for the protection and sustainability (Sánchez-Cordero et al., 2005; Martinez-Meyer et al., 2006; Rana et al., 2020). Species distribution modeling (SDM) is a valuable tool for assessing the impact of climate change on the distribution patterns of useful plant species, which is essential for conservation planning (Kumar, 2012; Ranjitkar et al., 2014; Rana et al., 2017). Species distribution modeling is supported in prioritizing conservation needs and provides a useful means of monitoring future surveys in predicted species distribution areas (Guisan and Thuiller, 2005).

In the last two decades, the use of SDM tools has increased rapidly for predicting species niche (Ranjitkar et al., 2014; Rana et al., 2017; Thapa et al., 2021). They are being used extensively in the field of conservation of valuable species, modeling species richness patterns, predicting future distribution, predicting the extent of species invasions and habitat suitability for mixed plantation climate change mitigation (Kumar, 2012; Ranjitkar et al., 2016; Rana et al., 2017). Various SDM methods including ensemble, machine learning, and statistical are in current use to model species distribution (Shrestha et al., 2014; Rana et al., 2020). Among them, we selected a machine learning method-MaxEnt, developed by Phillips et al. (2006) and have been widely used to predict species

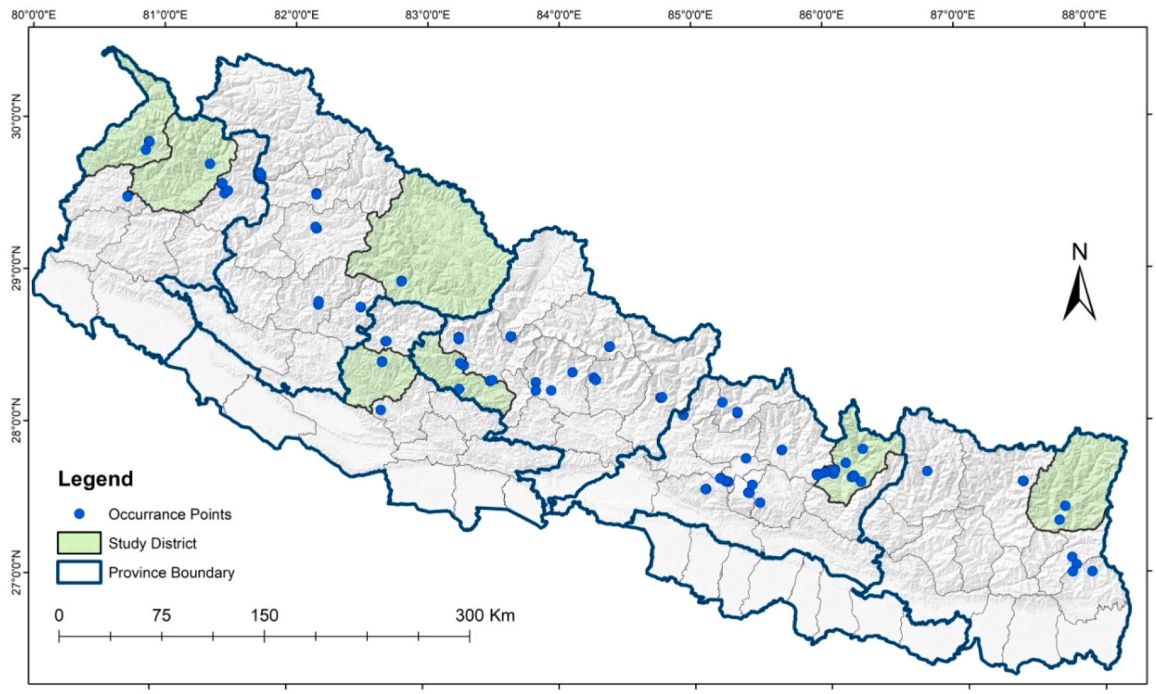

Fig. 1. Map of Nepal showing districts, the occurrence of *A. costatum* (blue dots) and sample districts for field verification (green color).

distribution (Phillips et al., 2008).

Present work focused on *Arisaema costatum*, which has multiple use value in the Himalaya. These wild species are ecologically and ethnobotanically very importance in the rural area of Nepal. Overexploitation and climate change has created a risk to *Arisaema*, which in turn can have profound impacts on biodiversity and local livelihoods (Charmakar et al., 2021; Kunwar et al., 2020; Matsumoto et al., 2020; Shrestha et al., 2022). Therefore, it is crucial to assess critical populations and habitats to protect species that are under immense collection pressure and ensure their future existence and survival. In Nepal, the assessment of climatic variables for modeling the habitat suitability of *A. costatum* is virtually non-existent. Thus, our study aims to investigate how climate change affects *A. costatum* in the present and future scenarios, in terms of potentially changing this population, distribution, production, and use. Simultaneously we aim to identify suitable climatic habitats for its future distribution under changing climate scenarios.

2. Materials and methods

2.1. Study area

We obtained species occurrence data from diverse sources, including published literature, reports, government herbaria, and personal records. For the collection of ethnobotanical data and assessment of ecological status, we randomly chose seven districts from the hill and mountainous regions spanning from the east to the west of Nepal. These districts are home to several indigenous and local communities, including Rai, Limbu, Thami, Gurung, Magar, Tamang, Jirel, Kshetri, and other cultural groups. Ground verification was conducted at various sites in the selected districts, namely Taplejung (Phungling Municipality, 1800–2900 m), Dolakha (Bhimeshor Municipality, 1750–2950 m), Baglung (Kathekhola Rural Municipality, 1860–2900 m), Rolpa (Thawang Rural municipality, 1870–2890 m), Dolpa (Thuli Bheri M unicipality, 1790–2900 m), Bajura (Gaumul Rural Municipality (1700–3000 m), and Darchula (Api Himal Rural Municipality, 1750–2950 m) (Fig. 1).

2.2. Study species

Arisaema costatum (Wall.) Mart. (Araceae, *Arisaema* Mart.) is an Asian species of perennial herbaceous plants. The native range of this species is Himalaya to Tibet (Govaerts et al., 2002; Ma and Li, 2017). Commonly found in Quercus-Rhododendron-Lyonia mixed forests, open meadows, and the slopes facing southeast of the Himalayas at altitude of 1900–2800 m (Polunin and Stainton, 1984; Shrestha et al., 2022). The species emerges in summer, goes through its life cycle, and then enters dormancy during winter, facilitated by its underground tubers. In Nepal, it is commonly referred to as "Banko" or "Sarpa ko makai" (snake's corn) due to its spadix resembling the head of a snake and its fruit looking like mature corn. Traditionally local people used whole plants for vegetables and medicine (Shrestha, 2009; Bhattarai et al., 2010). Due to harvesting of whole plants (tubers/corm and aerial) parts, the natural populations are rapidly decreasing in the Nepal Himalaya.

2.3. Data collection

Both qualitative and quantitative research methods were utilized to analyze both primary and secondary data in this study. The research was conducted in seven regions of Nepal, covering Taplejung, Dolakha, Baglung, Rolpa, Dolpa, Bajura, and Darchula, from 2019 to 2022. Its purpose was to collect data on the distribution of the population, harvesting practices, traditional uses, and processing techniques of "Banko". To conduct the study, we obtained permission from the department of forest and environment, and we ensured that all respondents gave their prior informed consent before conducting interviews and meetings. We also explained the research objectives to the participants. We utilized various data collection techniques such as focus group discussions, key informants' interviews, individual interviews, and field observations to gather primary information. We collected basic information using semi-structured questionnaires on *A. costatum* including the Divisional Forest Office at each district ($n = 7$), traders at district collection center ($n = 14$) and local collectors ($n = 189$, including headers and healers) at community and site level. We asked six questions to assess the purpose, level of harvest and treatment of *A. costatum*: (a) Do you harvest *A. costatum*? (b) If yes, then for what purpose (only for domestic utilization or also for selling)? (c) How much quantity do you typically collect in a season? (d) Is *A. costatum* poisonous in the raw form, to animals and humans? (e) If yes, how is it fermented/detoxified? and (f) How do you treat humans and domestic animals if they accidentally eat this plant before fermentation or in its raw state?

2.4. Plot establishment and sampling

During the peak growing season of *A. costatum* from June to October between 2019 to 2022, we conducted a sample-based study. We examined the geographical distribution of *A. costatum* across seven districts, namely Taplejung, Dolakha, Baglung, Rolpa, Dolpa, Bajura, and Darchula, with an elevation range from 1900 to 2800 m. To do this, we laid out five transects in each population at an interval of 200 m, following the guidelines set out by Government of Nepal (GoN, 2012). A total of 280 quadrats, each measuring 2×2 m, were sampled. In each transect, we set up eight plots, each at least 40 m apart from each other, depending on the field conditions. We then systematically sampled these plots and measured all the physical and biological variables. This resulted in a total of 280 plots, with 40 plots in each district. Using the Non-timber forest products (NTFPs) guidelines of Nepal (GoN, 2012), we calculated the fresh and dry mass production, which enabled us to determine the population density and dry yield of the species. Density of the *A. costatum* population along the elevation was evaluated by conduct in SPSS 24 (IBM, Armonk, NY, USA).

2.5. Modeling distribution

To model the potential ecological distribution of *A. costatum* in Nepal, we compiled a dataset of 196 ground cover occurrence points from a combination of field surveys and secondary sources (Fig. 1). These points were utilized for our modeling efforts. Our dataset consisted of 105 occurrence points from physical observations conducted across seven districts, seven records from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org, accessed on 7th July, 2022), 19 from the National Herbarium and Plant Laboratories, three from Flora of Nepal (https://floraofnepal.org/data/specimens), and 65 points collected by the authors themselves during their duration of other fieldwork in various districts, including Bajhang, Humla, Mugu, Baitadi, Rukum West, Pyuthan, Myagdi, Kaski, Dhading, Rasuwa, Sindhupalchok, and Sankhuwasabha.

After collecting the location data, we utilized spatial rarefaction along a 1 km grid to reduce model bias and interpret spatial autocorrelation (Rana et al., 2020). We obtained current conditions data (1970–2000) and future climate data for the 2050 s and 2070 s, along with 19 bioclimatic variables (BIO01-BIO19), at a resolution of 30 arc-seconds (approximately 1 km^2) from the WorldClim website (https://worldclim.org/data/index.html, accessed on July 16th, 2022) (Fick and Hijmans, 2017). Additionally, we extracted ground elevation data from a digital elevation model (http://ita.cr.usgs.gov). We utilized MaxEnt modeling (version 3.4.4; https://biodiversityinformatics.amnh.org/open_source/maxent/, accessed on July 18th, 2022) to determine potential suitable habitats under two shared socioeconomic pathway scenarios (SSP2–4.5: Intermediate forcing category, radiative forcing reaches 4.5 W/m^2 in 2100; SSP5–8.5: High forcing category, radiative forcing reaches 8.5 W/m^2 in 2100) for various time periods (present, 2050 s, and 2070 s) (O'Neill et al., 2016).

We evaluated for multicollinearity among the 19 bioclimatic variables and removed those with high correlation ($r > .70$). We used seven remaining variables - annual mean temperature (BIO1), mean diurnal range (BIO2), isothermality (BIO3), temperature annual range (BIO7), precipitation of driest month (BIO14), precipitation of warmest quarter (BIO18), precipitation of coldest quarter (BIO19), and physiographic variables (elevation) - as predictors. We used 70% of occurrence data for model calibration and the remaining 30% for model validation. Species presence data was prepared, and the model utilized logistic output with a random test percentage set at 25% and a training percentage of 75%. We ran the model with 5000 maximum iterations, 10 replicates in a bootstrap replicate type, a regularization multiplier of 1, convergence threshold of 0.00001, and a maximum figure of background points of 10,000. We utilized linear, quadratic, product threshold, and hinge features (Rana et al., 2017).

The suitability of habitats for *A. costatum* was determined by reclassifying MaxEnt output data using a specific threshold based on maximum training sensitivity, as described by Xu et al. (2019). A spatial analysis was then conducted in ArcGIS to extract a species distribution map for *A. costatum* in present, 2050, and 2070. MaxEnt data range from 0 to 1, with 0 indicating the lowest and 1 indicating the highest probability of distribution. Predicted habitat suitability was used to define four arbitrary classes: no suitability (0–0.25), low suitability (0.25–0.50), medium suitability (0.50–0.75), and high suitability (>0.75), according to Rana et al. (2020). Model evaluation was performed using the receiver operating characteristic (ROC) curve and the area under the ROC curve (AUC) value. The AUC value ranges from 0.5 to 1.0, with 0.5 indicating a random prediction and 1.0 indicating perfect model performance. Model performance was categorized into five levels: poor reliability (<0.7), fair reliability (0.7–0.8), good reliability (0.8–0.9), and excellent model prediction (0.9–1.0), as described by Swets (1988), Elith et al. (2006), Karami and Mirsanjari (2017), and Ye et al. (2020).

3. Results

3.1. Production, collection, processing, use and trade

The density of plants differed across the districts, with the population of *A. costatum* being denser in Baglung than in other districts. On average, the occurrence density of *A. costatum* was 0.75/m^2 and the annual dry mass production was 103.65 kg/ha (mean) across seven districts (Table 1). In 560 microplots, 210 individuals of *A. costatum* were observed, indicating a moderate level of richness in *A. costatum* across the sample districts (0.75 plants/m^2). Of the 210 respondents we interviewed, approximately 70% ($n = 147$) reported harvesting *A. costatum* for personal use as a vegetable, while 28% ($n = 59$) harvested it for both personal use and trade. The remaining 2% ($n = 4$) were aware of the uses of *A. costatum* but had never harvested it themselves.

Table 1
Occurrence density and dry yield of *A. costatum* in different districts of Nepal.

District	No. of plants (/ha)	Total fresh weight (kg/ha)	Conversion factor*	Total dry yield (kg/ha)
Taplejung	7,000	987.00	0.0979	96.62
Dolakha	7750	1092.75	0.0979	106.98
Baglung	8313	1172.13	0.0979	114.75
Rolpa	7438	1048.69	0.0979	102.67
Dolpa	7063	995.88	0.0979	97.50
Bajura	7625	1075.13	0.0979	105.25
Darchula	7375	1039.88	0.0979	101.80
Average	7509	1058.76	0.0979	103.65

* Conversion factor was calculated by dry weight (13.8 g)/ fresh weight (141 g).

Our research revealed that the fermentation processing technique for *A. costatum* was passed down orally and practically from one generation to the next. The local people would collect the aerial parts (stem and leaves) from the wild habitat during June and July. They would then use a wooden or iron hammer to pound the parts (Fig. 2A, 2B), ensuring that the stem and leaves were not detached from each other so that pounded plants can be hung easily to dry. The pounded parts were then sun-dried for 2-3 days to wilt and reduce moisture content. The pounded parts were then placed in a container, such as a plastic bag or sac, wooden, earthenware, or glass jar, and compressed tightly. The rim of the container was closed tightly, and it was placed in a safe and sunny location. If the crushed parts were kept in a plastic bag or sac, they were buried in about 80 cm height and 60 cm diameter cattle manure pit (a mixture of cattle dung, urine, and dry leaves). The plastic sac was then left to process for 5-7 days and then removed from the pit and then again dried in the sun for a few days for complete removal of the moisture. The final product was called "Gundruk" or "Sinki" of Banko (product local name varied from place to place) and was stored at room temperature for future consumption (Fig. 2C).

Our research found that only approximately 13% (n = 27) of *A. costatum* users harvested both parts (tubers or corm and aerial parts). The tubers or corm were harvested from the wild between November and April. To make it safe to eat, *A. costatum* was boiled with 2 spoonful of salt and 8–10 spoonful of ash dust for about an hour over a strong flame. The outer layer of the tubers was then peeled off, and the inner mass was eaten with a spicy pickle/sauce made from a mixture of garlic, salt, vinegar, and rattan pepper.

Rural communities across seven districts typically processed the stem and leaves of *A. costatum* for household use, while tubers were primarily utilized in Baglung, Rolpa, Dolpa, Bajura, and Darchula. Most of the respondents reported using the plant for making Gundruk, a dried vegetable, for their own consumption. In Baglung, however, the aerial parts were also collected for commercial

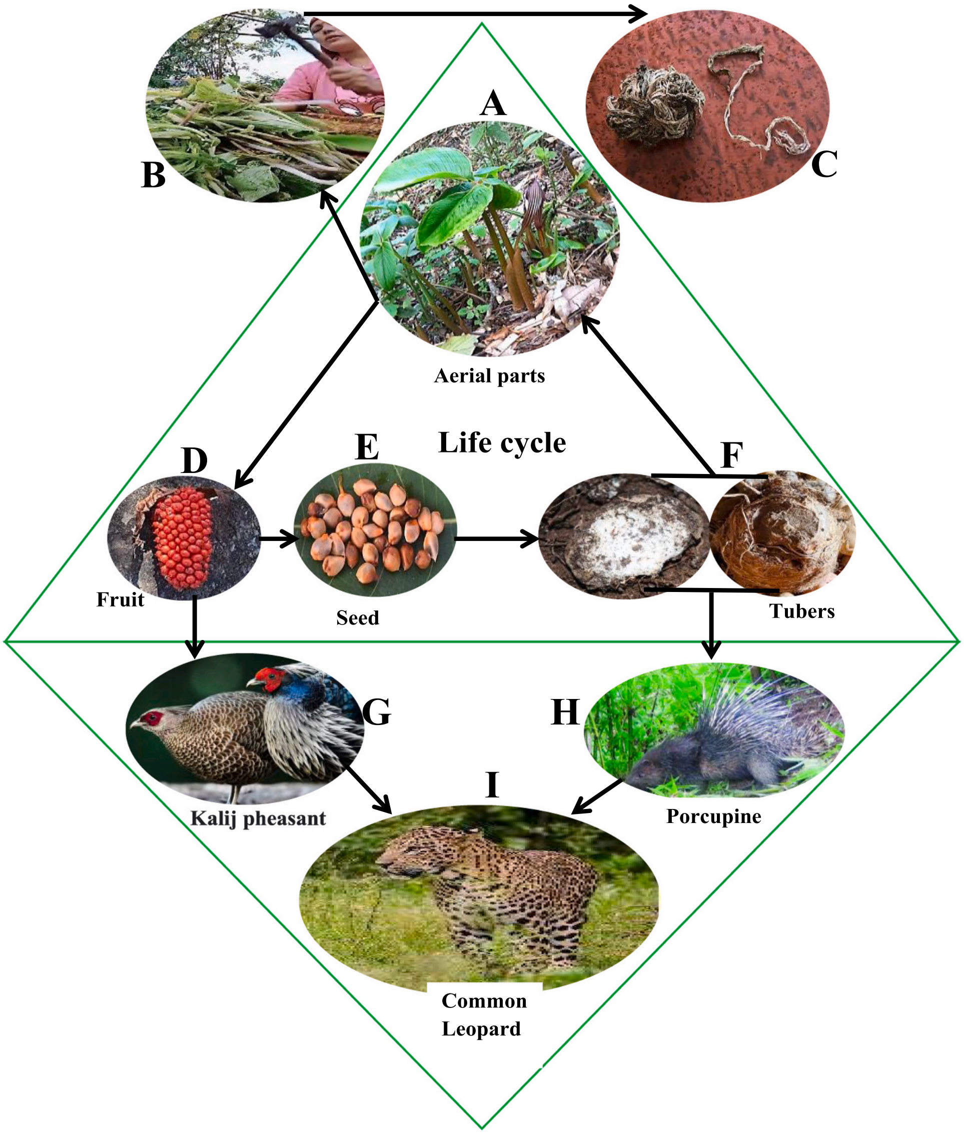

Fig. 2. *A. costatum* life cycle and used by different organisms (Photos A-F from field visit and G-I from Google.com).

purposes, with the final product ("Sinki" or "Gundruk") sold for at NPR 2000/kg in the local market. Respondents emphasized that *A. costatum* was initially poisonous but safe to consume after processing the stem, leaves, and tubers. They further revealed that the plant had medicinal properties and was used to treat stomach disorders, gastritis, and asthma by 90% of the respondents (n = 190).

Our study found that male respondents (n = 116) believed that ripe fruits (Fig. 2D) of *A. costatum*, available from August to November, were a valuable source of food for endangered and vulnerable frugivore bird species such as Hill partridge (*Arborophila torqueola*), Satyr Tragopan (*Tragopan satyra*), Kalij pheasant (*Lophura leucomelanos*), Cheer pheasant (*Catreus wallichii*), and Himalayan monal (*Lophophorus impejanus*). Some of the respondents (n = 7) have suggested that frugivorous birds play a crucial role in seed dispersal for *A. costatum*. This plant species not only supports the survival of frugivorous birds but also benefits from the birds' role in propagating its population through seed (Fig. 2E) dispersal. Additionally, a small percentage (n = 13) of elderly males (above 50 years age) reported that Porcupines (*Erethizon dorsatum*) consumed the underground tubers (Fig. 2F) throughout the year. We interviewed staff at the Divisional Forest Offices in the seven study districts. They confirmed that the wild birds (Fig. 2G) and Porcupines (Fig. 2H) are significant prey for the common leopard (*Panthera pardus*) (Fig. 2I), as per our findings from the local communities.

3.2. Treatment practice against the poisonousness of A. costatum

We found that the entire raw plant was poisonous in nature to both humans and domestic animals, including cows, buffaloes, sheep, and goats. The vibrant and visually appealing nature of fruits can capture the attention of both young children and newborn animals, leading to unintentional consumption on occasion.

After ingestion, symptoms for both animals and humans included swelling tongue and the continuous release of saliva, vomiting, and difficulty breathing are observed. In addition to these symptoms, humans also experienced itching and skin allergies. When symptoms appear, local people typically treat the allergic reaction of plant by using salt, sugar, and edible vinegar or lemon juice/lemon concentrate or a combination of all in specific doses (Table 2) for both humans and animals. Among the respondents, 7% (2.14 ± 0.40) used sugar solution, 8% (2.43 ± 0.29) used salt solution, and 10% (3.00 ± 0.61) used vinegar solution. Additionally, 11% (3.43 ± 0.64) used a mixture of sugar and salt, 14% (4.14 ± 0.40) used a mixture of sugar and vinegar, 17% (5.00 ± 0.53) used a mixture of salt and vinegar, and 25% (7.57 ± 0.48) used a mixture of sugar, salt, and vinegar. However, 8% (2.29 ± 0.28) of the respondents were unaware of any treatment for the poisoning (Fig. 3).

Among them, 13% used medicinal plants such as garlic (*Allium sativum*), rattan pepper (*Zanthoxylum armatum*), and love apple (*Paris polyphylla*). A mixture of medicinal plants is combined to create a paste. For domestic animals, small pieces, about the size of a pea, are extracted from the mixture and then wrapped in the animals' preferred grass leaves and fed them. This process is repeated four times a day to administer the paste to the domestic animals. This herbal dose used for both humans and animals are the same.

3.3. Distribution, habits, and key variables

We observed *A. costatum* in 29 hills and mountainous areas, all within a narrow elevation range of 900 m, ranging between 1900 and 2800 m. The maximum occurrence was recorded at 2400 m with 28.00 ± 1.03, followed by 25.25 ± 1.12 at 2200 m, 21.75 ± 1.35 at 2600 m, 16.25 ± 1.53 at 2000 m, and 13.87 ± 0.44 at 2800 m (Fig. 4). The species was found on slopes ranging from gentle to steep, mainly facing north-east and south-east of the hills and mountains of Nepal. It was commonly found in open meadows and under the canopy of mixed *Rhododendron arboretum, Quercus semecarpifolia, Lyonia ovalifolia*, and *Laurel* forests. The most frequently associated species were *Centella asiatica, Galium aparine, Oxalis corniculata, Anemone rivularis, Fragaria nubicola, Selaginella species, Imperata cylindrical,* and *Viola canescens*.

After conducting the Jackknife analysis test, eight variables were selected based on their contributions to modeling *A. costatum* (Table 3). Among these variables, elevation (a topographic variable) had the highest contribution (54.2%), followed by annual mean temperature (BIO-1) (22.3%) and precipitation of the warmest quarter (BIO-18) (15.2%). On the other hand, the mean diurnal range (mean of monthly (max. temperature – min. temperature)) (BIO-2) had the lowest contribution (0.2%). In total, climatic variables accounted for 45.8% of the modeling contribution. Model accuracy and prediction success were evaluated using threshold-independent measures such as AUC, with an average value of 0.94 ± 0.02 under different SSPs and current conditions.

Currently, *A. costatum*'s the most suitable zones (indicated in red on the map) are primarily distributed in the central regions of Nepal, spanning from east to west and excluding alpine and tropical elevation zones (Fig. 5). Based on the current climate conditions, only 14% (21,121.75 km^2) of Nepal's total area is deemed suitable for *A. costatum*, with 2% being highly suitable, 6% moderately suitable, and 7% low suitable, while the remaining 86% is unsuitable (Fig. 5). In terms of topography, the temperate regions of the

Table 2
Traditional treatment doses for *A. costatum* ingested by humans and animals.

Materials used	Quantity (spoonful)	Water (ml)	Dose (/day)
Sugar	1	300	3
Salt	1	300	3
Vinegar	1	300	3
Sugar and salt	1 + 1	300	2
Sugar and vinegar	1 + 1	300	2
Salt and vinegar	1 + 1	300	2
Sugar, salt, and vinegar	1 + 1 + 1	300	1

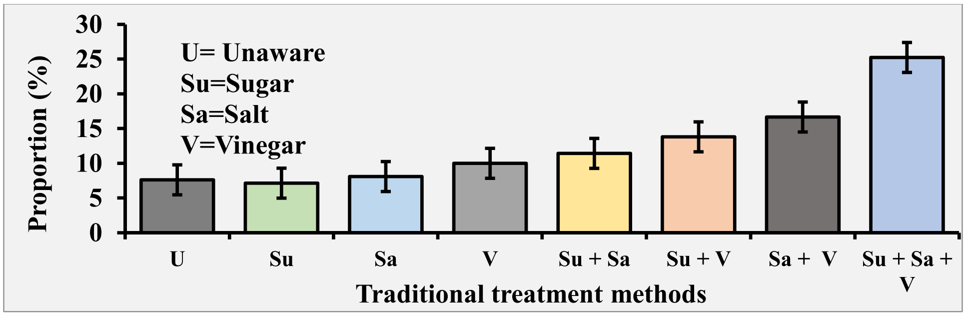

Fig. 3. Proportion of traditional treatment methods preferred according to local respondents.

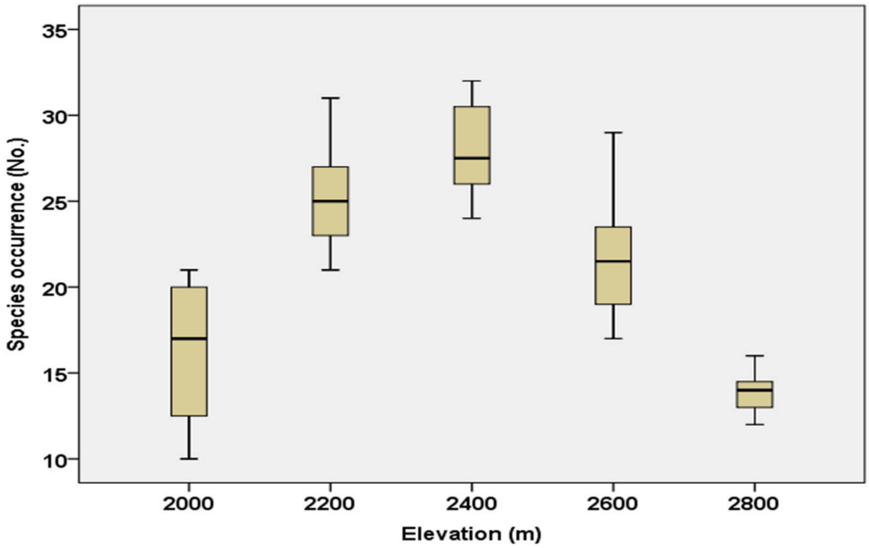

Fig. 4. Occurrence of *A. costatum* along the elevation range in seven districts.

Gandaki, Bagmati, and Koshi provinces (shown in red on the map) are predicted to be highly suitable habitats for *A. costatum*, in comparison to the western provinces of Nepal (Fig. 5).

The suitability of *A. costatum*'s habitat was determined based on eight variables, among which elevation, annual mean temperature, and precipitation of the warmest and coldest quarters were found to be the most significant. As depicted in the response curve (Fig. 6A), *A. costatum* exhibited a preference for elevations of around 2400 m. Moreover, the annual mean temperature of approximately 15 °C (Fig. 6B) was found to be conducive to its habitat. The precipitation of the warmest quarter of about 1400 mm (Fig. 6C) and the coldest quarter of less than 15 mm (Fig. 6D) (indicating a low coefficient of variation in precipitation) were identified as the most suitable conditions for *A. costatum*.

Table 3
Estimates of relative contribution and permutation importance of the environmental variables to the Maxent model.

Environmental variables	Contribution (%)	Permutation importance[a]
Altitude	54.2	85.64
Annual mean temperature (BIO-1)	22.3	8.62
Precipitation of warmest quarter (BIO-18)	15.2	2.30
Precipitation of coldest quarter (BIO-19)	5.2	0.99
Isothermality (BIO2/BIO7) (×100) (BIO-3)	1.5	0.87
Precipitation of driest month (BIO-14)	1.1	1.01
Temperature annual range (BIO5-BIO6) (BIO-7)	0.2	0.47
Temperature annual range (BIO5-BIO6) (BIO-7)	0.2	0.47
Mean diurnal range (mean of monthly max. temperature – min. temperature) (BIO-2)	0.2	0.10

[a] Permutation importance of each variable were obtained using the jackknife test in MaxEnt model.

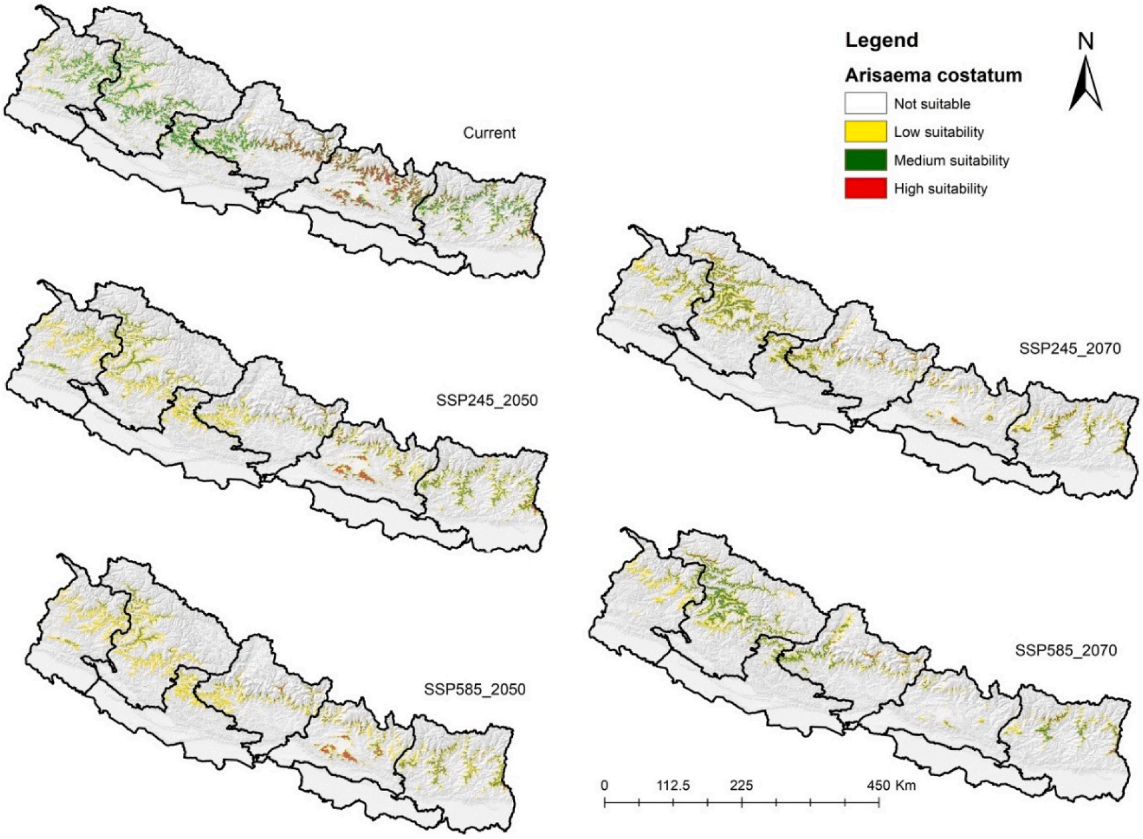

Fig. 5. Change in the current habitat suitability of *A. costatum* in Nepal with future climate in different SSPs: Red regions predicted most suitable (>75% probability), green region represents the moderately suitable (25–49% probability) and yellow region represent least suitable (<25% probability) habitat.

3.4. Change in suitable area in future scenarios

According to the findings presented in Fig. 7, it is projected that the total suitable habitat will experience a net shrinkage ranging from 4.5% to 4.9% by 2050 and 5.2% to 6.2% by 2070 under both SSP2–4.5 and SSP5–8.5 scenarios. Additionally, highly suitable areas are expected to gradually decrease from 0.1% to 1.7% in both 2050 and 2070.

Conversely, low suitable areas are projected to increase by 0.2% and 0.6% by 2050 in SSP2–4.5 and SSP5–8.5 scenarios, respectively. In the SSP2–4.5 scenario, moderate suitable areas are predicted to decrease by 3.5% and 2.4% by 2050 and 2070, respectively, while in SSP5–8.5, the moderate suitable habitat is projected to decrease by 4.1% and 2.9% in 2050 and 2070. Overall, both scenarios indicate a gradual decrease in highly and moderately suitable habitats, while there is a slight increase in low suitable areas by 2050 and 2070.

4. Discussion

The consumption of wild edible plants is a widespread practice that serves as a crucial element of ecosystem-based adaptation and food security in many regions of the world (Fernald and Kinsey, 1943; Quave and Pieroni, 2015; Uchida and Kamura, 2020). In Nepal, where wild edible plants are a vital source of sustenance for many rural communities facing economic hardship (Acharya and Acharya, 2010; Khakurel et al., 2021), this study investigates the local management and use of *A. costatum* as a wild edible vegetable and herbal medicine. Our research collected information from across Nepal, revealing an average annual production of 103.65 kg/ha of dried aerial parts (stem and leaves) of *A. costatum*, with a maximum of 114.75 kg/ha in the Baglung district and a minimum of 96.62 kg/ha in the Taplejung district. Despite its poisonous nature in its natural state, local people consume *A. costatum* (aerial parts and corm) in significant amounts due to its affordability and accessibility. To render the plant safe for consumption and preserve it for long periods, local people employ traditional fermentation techniques to convert *A. costatum* into a dry vegetable (Bhattarai, 1991; Khakurel et al., 2021). The fermented product is also used medicinally to treat ailments such as stomach disorders, gastritis, and asthma (Shrestha and Dhillion, 2003).

According to key informants, the harvesting time for *A. costatum* varies depending on the growth of its corm and aerial parts. Aerial parts are typically harvested during the rainy season (June-July), coinciding with the re-sprouting, flowering, and fruiting of other wild

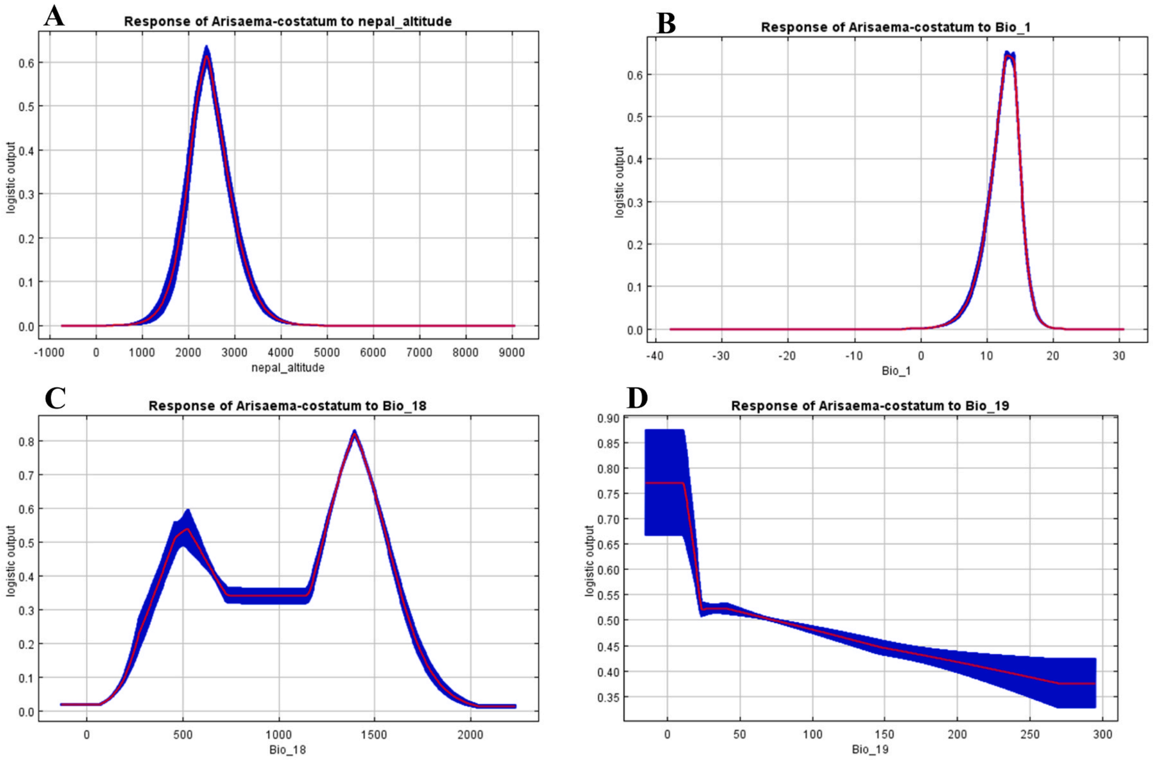

Fig. 6. The response curves of the four most important variables governing habitat suitability of *A. costatum*. (A) Prefers elevations around of about 2400 m, (B) Bio 1 indicates annual mean temperature (suitability peaks at around 15 °C), (C) Bio 18 indicates precipitation of warmest quarter (suitability peaks at higher precipitation 1400 mm), and (D) Bio 19 indicates precipitation of coldest quarter (suitability peaks around the value <15).

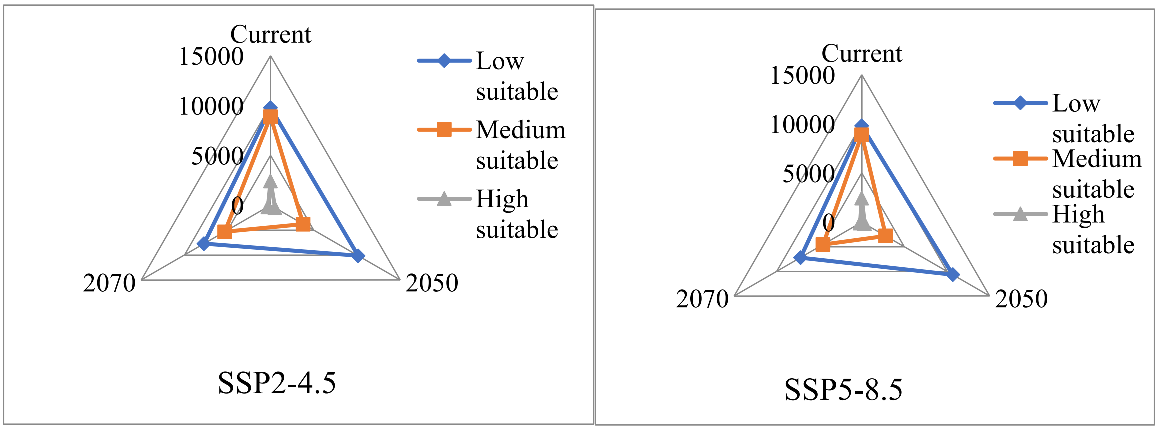

Fig. 7. Projected suitable areas for *A. costatum* under present condition and two climate change scenarios (SSP2–4.5 and SSP5–8.5) for the year 2050 and 2070. The X- axis represents the year and the Y-axis represents the area.

edible plant species, thus increasing their availability (Oishi et al., 2020). During this season, households have a wide range of crop options, but wild plants like *A. costatum* remain important. Worldwide, people harvest, ferment, and store wild edible vegetables primarily during the rainy season (Pieroni and Quave, 2005; Chauhan et al., 2018). In contrast, during the dry season, communities rely solely on stored food and wild edible vegetables like *A. costatum*'s tuber or corm. In Nepal, we observed rural people using fermented aerial parts and tubers or corms of *A. costatum* during the dry season when cultivated vegetable production is often insufficient to meet demand throughout the year. Wild vegetables like *A. costatum*, fill this gap (Burlingame, 2000; Bhattarai et al., 2009). *A. costatum* and other wild edible plants are vital in meeting the daily food requirements of rural communities in the studied districts, playing a significant role in their survival strategies (Aryal and Kreigenhofer, 2009; Dorji, 2012; Addis et al., 2013). Not only are wild edible plants crucial in times of famine or stress (Ong and Kim, 2017), but they are also an essential part of a mineral-rich normal diet for millions of people (Bharali et al., 2017).

In our study districts, the local people employ a traditional method to ferment *A. costatum*, which has been orally and practically passed down from generation to generation. The identification, collection, and preparation of wild food requires both traditional and ecological knowledge (Pilgrim and Wyss, 2008). The *A. costatum* leaves and stem are harvested from the wild and then pounded with a wooden hammer before being sun-dried for 2–3 days to remove moisture. They are then naturally fermented through a process of dumping until they acquire a characteristic aroma and a typical sour taste. After completion of the week-long fermentation process, the "Gundruk" or "Sinki" (local name of the final product) is removed from the pit, sun-dried, and stored at room temperature for future consumption. Using the same procedure, every leafy wild and cultivated vegetable could be made into "Gundruk" from Arums (*A. utile* and *A. flavum*), watercress (*Nasturtium officinale*), blister buttercup (*Ranunculus sceleratus*), turnip (*Brassica rapa* subsp. rap), radish (*Raphanus raphanistrum subsp. sativus*) and cabbage/cauliflower (*Brassica oleracea* var. capitata) (Bhattarai, 1991; Dahal et al., 2005). In the same vein, when it comes to detoxing root vegetables such as tubers or corms, they are made edible by boiling them over a high flame and adding either two spoonful of salt or eight to ten spoonful of cattle dung ash dust for about an hour. After boiling is over, the outer layer of the tubers is peeled off, and the inner part is consumed with a sauce made from garlic, salt, vinegar, and rattan pepper. Like our findings, Manandhar (2002) reported that *Arisaema tortuosum* corms are consumed in various districts of the Nepal Himalayas, in addition to *A. costatum*.

A. costatum serves not only as a valuable food source for humans, but also for endangered and vulnerable frugivorous wildlife in Nepal's hill and mountain regions. According to Natarajan (1992), bird species diversity and populations depend on climate conditions and the availability of food sources. In Nepal's temperate region (2000 m – 3000 m), forests with abundant food sources, such as *A. costatum*, are crucial for supporting bird species richness (Jha, 2019; Inskipp et al., 2020). Wild birds that feed on fleshy-berry fruits play a crucial role in seed dispersal for *Arisaema* (Oishi et al., 2020; Maeda and Takahashi, 2021). These seeds stay in the birds' digestive system for a few days and when the seeds are fertilized through bird droppings, there is a significant increase in seedling growth (Devkota, 2005; Jordano et al., 2007; Tsunamoto et al., 2020).

In addition to this, porcupines have a diverse range of habitats, hence the temperate region is also considered as the suitable habitat due to variety of food availability, including the corm/tubers of *A. costatum*, and suitable climate conditions (Jnawali et al., 2011). *A. costatum*, therefore, plays a critical role in the survival and population of wild birds and Porcupines in the Himalayas' temperate region. Human beings, frugivorous wild birds, and Porcupines control the population of *A. costatum* in their natural habitats. Meanwhile, the common leopard controls the populations of frugivorous wild birds and Porcupines and feeds on them as they make up about 60% of the leopard's diet (Aryal and Kreigenhofer, 2009; Kandel et al., 2020). As a primary producer, *A. costatum* plays an essential role in the food chain and food web of the Himalayan ecosystem. *Arisaema* species are contributing directly or indirectly to the conservation of the common leopard, frugivorous wild birds, and porcupines in their habit (Suzuki and Maeda, 2014a; Baral et al., 2023).

A. costatum is a poisonous plant that poses a serious risk of accidental poisoning to children and domestic animals. Although the local population is generally aware of this issue, there are other poisonous plants, such as *Aconitum ferox, Datura stramonium, Colocasia* sp, *Lyonia ovalifolia, Pieris formosa*, and other species of *Arisaema* that also pose a threat (Bhandari and Shrestha, 1985; Knight and Walter, 2001; Heckel et al., 2010; Suzuki and Maeda, 2014b). Symptoms of poisoning include generalized weakness, swollen tongue, continuous release of white bubble saliva, vomiting, difficult breathing, and even death. Respondents reported using a solution of sugar, salt, and vinegar diluted in water at various concentrations, as well as medicinal plants like Garlic (*Allium sativum*), Rattan pepper (*Zanthoxylum armatum*), and Love apple (*Paris polyphylla*) to treat accidental ingestion. They also prepared a paste from these medicinal plants and wrapped it in a favorite grass leaf, which was given to domestic animals four times a day. These traditional methods of treatment are effective, as there is no known specific antidote for *A. costatum* poison. However, prevention is crucial, and it is important to educate children, adolescents, and parents about the potential risks of toxic plants (Joshi and Joshi, 2000; Sharma et al., 2022).

Our research investigated the potential distribution of *A. costatum* in Nepal under current and future climatic conditions. We found that elevation was the most significant factor, accounting for 54.2% of the prediction scores, followed by temperature and precipitation. Our study revealed that *A. costatum* prefers elevations around 2400 m, as demonstrated by our response curve and recent collection records from the seven study districts. This suggests that elevation, as a non-climatic environmental variable, has a significant influence on species distribution in the Nepal Himalayas, which is consistent with the findings of previous studies (Thapa et al., 2021; Cahyaningsih et al., 2021; Kunwar et al., 2023). However, our results contradict the findings of Blach-Overgaard et al. (2010).

We also found that elevation played a crucial role in predicting the future distribution of plant species in India (Kaliyathan et al., 2016) and the Nepal Himalayas (Kunwar et al., 2023). Temperature-related variables, such as annual mean temperature, temperature annual range, and mean diurnal range (BIO-1, BIO-7, and BIO-2), accounted for up to 22.8% of the distribution of *A. costatum*. Similarly, temperature-related variables were found to be more responsive in determining suitable habitat for plant species in the Himalayas (Rana et al., 2020; Rawat et al., 2021; Kunwar et al., 2023). According to Chhetri et al. (2018), temperature-related climatic variables and elevation play a crucial role in species distribution in the Nepal Himalayas.

Precipitation-related variables, such as precipitation of the warmest and coldest quarter, contributed up to 20.3% to the distribution of *A. costatum*. Precipitation of the warmest quarter (BIO-18) was particularly important because *A. costatum* requires a significant amount of rainfall during the wettest month to survive, grow, and reproduce in the Nepal Himalayas. Our findings are consistent with the requirements of many other plant species in Nepal (Rana et al., 2020; Kunwar, 2021), which also need a large amount of rainfall during the wettest month.

The suitable area for *A. costatum* is projected to shrink by 2050 and 2070 under SSP2–4.5, with significant loss under SSP5–8.5 (extreme climate change). This trend is consistent with previous studies (Thapa et al., 2021; Wani et al., 2022; Kunwar et al., 2023) and highlights the increasing contraction of suitable areas for valuable plant species in Nepal. The Lumbini, Karnali, and Sudurpashchim provinces are expected to experience significant loss of *A. costatum* due to future climate change, especially under extreme carbon emission scenarios. The MaxEnt model showed AUC values above 90% for both current and future scenarios, indicating a decreasing climatically suitable habitat for Nepal's Himalayan region. Wiens (2016) reports that about 39% of alpine-temperate plant species in Nepal are affected by climate change, and further impacts may result from anthropogenic influences and biological invasion (Shrestha et al., 2021). Invasive species from southern regions aggressively occupy niches in sub-tropical and temperate areas, limiting the space for useful plant species (Bhattarai et al., 2014; Baral et al., 2017; Shrestha et al., 2018; Acharya et al., 2022). This situation is concerning for Nepal's plant diversity and ecosystem stability.

In the context of the conservation and management, *A. costatum* is a poisonous plant with potential harm to children and domestic animals when consumed in its natural form, undergoes a transformative process through fermentation, emerging as a crucial source of wild vegetables in rural Nepal. These wild edible plants, including *A. costatum*, play a pivotal role in meeting the daily food requirements of numerous inhabitants in rural villages, constituting essential components of their survival strategies. Their significance extends beyond times of famine, as they form an integral part of the mineral-rich normal diet for millions of people, highlighting their broader importance in sustaining human populations (Dorji, 2012; Addis et al., 2013; Bharali et al., 2017).

Furthermore, *A. costatum* not only benefits humans but also serves as a vital food source for endangered and vulnerable frugivorous wild birds and porcupines in the hills and mountains of Nepal. The common leopard, a key species in the region, relies on *Arisaema* as approximately 60% of its diet comprises wild birds and animals, emphasizing the plant's crucial role in their conservation efforts. The interdependence between the survival of the common leopard, frugivorous wild birds, porcupines, and the presence of *A. costatum* underscores the profound impact on their well-being in the Himalayan ecosystem. However, the suitability of *A. costatum*'s habitat is projected to decline significantly due to climate change, amplifying the urgency to address this environmental threat as it directly affects the distribution of valuable plant species. Adding to the challenges, local human populations in Nepal's mountainous areas, reliant on these plants for livelihoods, further intensify the pressure on the local habitat, rendering *A. costatum* and other wild edible plants more susceptible to endangerment (Colwell et al., 2008; Pyakurel et al., 2019; Kunwar et al., 2022).

5. Conclusion

Our research sheds light on the ecological distribution, population, habitat conditions, and usage of *A. costatum* in Nepal's temperate region. *A. costatum* is a plant with poisonous properties prior to fermentation and traditional way of treatment if accidentally ingested by domestic animals and humans are also discussed. However, after fermentation, it transforms into a medicinal plant that serves as a vital but underutilized resource. It plays a significant role in enhancing food and nutrition, generating income, and ensuring health security for households in the Nepal Himalayas. Furthermore, *A. costatum* serves as a fundamental source of diet for numerous endangered and vulnerable frugivorous birds and Porcupines, which, in turn, are preyed upon by common Leopards. Thus, it can be inferred that *A. costatum* plays a pivotal role in the Nepalese hills and mountains' ecosystem, as it is a critical component in completing the food chain. Our study also reveals that elevation, annual mean temperature (BIO-1), and precipitation of the warmest and coldest quarters (BIO-18 and BIO-19) are the key factors contributing to the distribution of *A. costatum* in Nepal. Our model indicates that approximately 14% of Nepal's land is suitable for *A. costatum*, with the temperate regions of Gandaki, Bagmati, and Koshi provinces being the most suitable. Under both the SSP2–4.5 and SSP5–8.5 scenarios, we project a net shrinkage of suitable habitat for *A. costatum* of 4.5% to 4.9% by 2050 and 5.2% to 6.2% by 2070, respectively, compared to the current habitat. This underscores the critical importance of physiography, annual temperature, and precipitation in predicting the future distribution of *A. costatum*.

Our findings have significant implications for ecologists, pharmacologist, planners, and policymakers in Nepal, as they provide a baseline database and initiate future strategies for the sustainable conservation of *A. costatum*. Urgent and integrated research (including its phytochemical and medicinal aspects) is needed as existing but insufficient data sheds light on the diverse species of *Arisaema* that hold medicinal significance and have been utilized for treating various diseases worldwide and progress programs are required to address the anticipated loss of *A. costatum* habitats and the potential increase in temperature due to climate change in the Nepal Himalayas.

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CRediT authorship contribution statement

Karki Sangram: Writing – review & editing, Methodology, Formal analysis. **Poudel Basu Dev:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Thapa-Magar Santosh:** Writing – review & editing, Investigation, Formal analysis. **Awasthi Manisha:** Writing – original draft, Writing – review & editing, Investigation, Conceptualization. **Chung Ki Wha:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ki Wha Chung reports article publishing charges was provided by National Research Foundation of Korea.

Data availability

Data will be made available on request.

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