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GENETIC DIVERSITY, PRODUCTION, AND TRADE OF CHILI WITH SPECIAL REFERENCE TO NEPAL

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SUMMARY

Chili is a popular spice crop in Nepal, a country with countless genetic diversity and a wider distribution covering areas from the tropics to the warm temperate regions. However, the exploitation of chili's genetic potential to improve yield has faced challenges by different factors. An analytical study on genetic diversity, production challenges, and marketing opportunities of chili was still lacking in Nepal. This study aims to provide information on chili diversity, its distribution, and uses in Nepal, discussing the potential role of chili in Nepalese agriculture. Mainly, the study is a desk review complemented with a field study. Total chili production increases with an increasing area under cultivation over the years. In 2021, chili production covered 23,083 ha, 13% higher than in 2020. Per capita chili consumption is estimated at 9.8 kg in 2021. Diversity in chili phenotypes grown in the study area of Nepal has been noted. On a nine-point scale, higher variations showed in fruit traits (5 ± 1.5), floral morphology (4 ± 0.8 distinct types of flowers), leaf size (3 ± 0.7), plant height (3 ± 0.8), and maturity (3 ± 0.8) among chili genotypes in the area studied. Insect pests (15.6%) and diseases (16.4%) emerged as the main problems in chili cultivation, followed by drought stress (14.8%) and a shortage of fertilizers (10.1%). Marketing-related issues shared 2.7% among the 12 main concerns, particularly farmers who suffered more from inadequate market information. In addition, estimates on seed requirements, seed sources, existing chili varieties, and market segments also gained focus. The need for demand-based action research to strengthen Nepalese chili production and marketing proves imperative to fulfill the growing domestic demand and export potential.

Keywords: biotic and abiotic stress; chili production issues; hot pepper; phenotypic markers; and phenotyping

Key findings: Nepal is rich in chili genetic resources, with records of notable phenotypic variations for fruit traits (average of five distinct shapes, sizes, and orientations in seven studied locations), for flower characters (average of four different colors and orientations), for leaf characters (average of three distinct sizes), for plant height (three different heights), and maturity (three levels of maturity) during the field study. Chili serves as the most significant spice crop in Nepal. The total area coverage and chili production increased over the years. In 2021, a larger area of more than 23,000 ha gained cultivation, producing nearly 184,900 MT and a per capita consumption estimated at 9.8 kg. The main culprits of the low productivity (8 ± 0.3 MT/ha) of chili in the country consist of biotic factors (insect pests and pathogens) (49%), abiotic factors (drought stress and fertilizer shortage) (40%), and managerial limitations (11%).

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INTRODUCTION

Chili (*Capsicum* spp.), originating from Latin America, is a well-known spice crop commonly grown worldwide for its spicy fruits. The genus *Capsicum* has a vast genetic diversity and demands standard references while studying species-specific traits. A total of 43 species of *Capsicum* attained identification. From these, five taxa (*C. annuum* L. var. *annuum*, *C. baccatum* L. var. *pendulum* (Willd.) Eshbaugh, *C. baccatum* L. var. *umbilicatum* (Vell.) Hunz. & Barboza, *C. chinense* Jacq., and *C. frutescens* L.) showed worldwide cultivation (Barboza *et al*., 2022). In Nepal, reports of three species include *C. annuum*, *C. baccatum,* and *C. frutescens,* and some collections on the border between the *C. annuum* and *C. frutescens-chinense* groups (Nemoto *et al*., 2016). The existence of chili genotypes that are near to or in between the groups indicates the genetic diversity due to natural crossings.

Growing local chili landraces and commercial cultivars throughout Nepal exists. Reports of chili cultivation occurred in 77 districts, ranging from subtropical to temperate agro-climatic conditions. To date, 16 chili varieties are listed at the National Seed Board for commercial purposes (SQCC, 2021), with three open-pollinated varieties (OPVs) including the first released variety, 'Jwala,' in 1994. Hybrid varieties occupy about 70% of the total cultivation area in Nepal. Chili is widely famous as a spice crop for fresh consumption, salads, vegetables, pickles, and natural color in foods. In 2021, vegetables occupied 9% of Nepal's total agricultural land and contributed to the national Agricultural Gross Domestic Product (AGDP) by 5.84%, with chili contributing 0.67%. The area of chili cultivation also increases with the increase in vegetable cultivation in the country. The agricultural land under chili cultivation reports approximately 23,000 ha (MoALD, 2022), which requires nearly 6 MT of seeds. However, chili seed production is limited to OPV, producing annually low (estimated at around 400 to 500 kg) (BK Upadhyaya, personal communication, October 20, 2022).

Chili consumption in Nepal has increased over the years, along with a growing trend in the use of spices. Spice use in Nepalese kitchens has increased from 4.45 kg per head per year in 2016 to 4.82 kg in 2019 (FAOSTAT, 2022). Chili serves chiefly as a spice crop, with a significant proportion used for fresh consumption (green and ripe), dried chili powder, and processed items, such as pickles, in the Nepalese context. Despite ethnicity, many Nepalese consume chili regularly. In particular, ethnic people of Kathmandu valley (Newars), Terai (Tharus, Rajbansis, etc.), and hills (Thakali, Gurung, Tamang, etc.) use chili in their traditional food items of cultural value. People use hot and spicy chili for its medicinal value, such as in treating neuropathic pain (Deka *et al*., 2016; Chung and Campbell, 2016). Local chili production is low compared with domestic demand. Good demand from the food industry is promising since chili provides a primary source of spicy condiments. Likewise, chili has wide use in the pharmaceutical industry to extract oleoresin (Bhadragoudar and Patil, 2011).

Despite the genetic resource diversity and economic potential of chili, Nepal's position in its production, use, and marketing still needs exploring. A Nepal-focused study of chili is scarce, and most chili-related research has studied and reviewed the Indian context (Colney *et al*., 2018). This article focuses on the genetic variation assessment of chili genotypes, with the vital issues of chili production discussed together with the potential contribution of chili to the Nepalese economy from the perspective of diversity, area coverage, yield, and use.

MATERIALS AND METHODS

The first part of the study evaluated the area and production of chili in the last four years (2018–2021) for the potential contribution of chili to the Nepalese economy. At the field level, assessing the genetic resource diversity of the chili genotypes took place by conducting a field study in seven districts, namely, Kathmandu, Bhaktapur, Makawanpur, Dailekh, Jhapa, Tehrathum, and Dhankuta (Figure 1). The purposive selection of the districts from east to west for the study resulted from the total chili production hectarage averaged from 2018 to 2020 (data source: MoALD, 2020). Out of the seven, two districts ranked high, three ranked middle, and two with lower rankings attained selection. Rapid Rural Appraisal (RRA), a tool suggested by Mwongera *et al*. (2017), collected firsthand information about

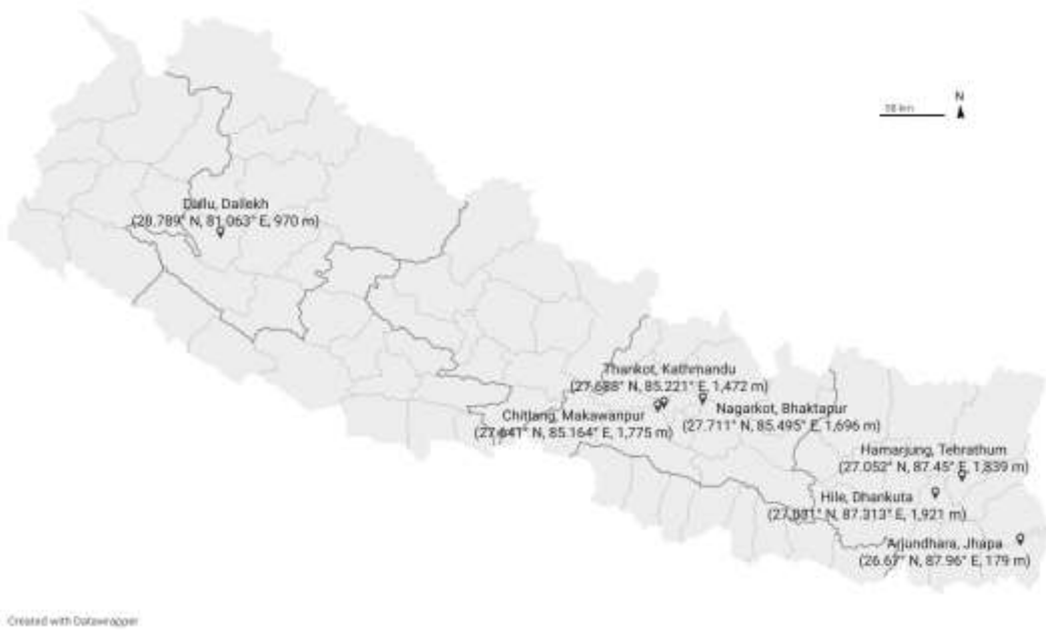

Figure 1. Nepal map showing the seven locations where the RRA was conducted in December 2020 and February 2021. The GPS coordinates and altitude in meters above sea level are shown in brackets. The map was created with Datawrapper, an online software developed by Datawrapper GmbH, Germany.

the genetic variations among chili genotypes, production, and marketing-related problems, uses, and the economic importance of chilies at sites studied. Using a semi-structured checklist for focus group discussions aided the RRA in December 2020 and February 2021. Updating the checklist progressed with the RRA, conducting key informant interviews and focus group discussions accordingly. Seven RRAs occurred as field studies at seven chili production sites in selected districts, covering 16 farmers from Makawanpur, 21 from Dailekh, 18 from Dhankuta, 17 from Jhapa, 15 from Kathmandu, 19 from Bhaktapur, and 14 farmers from Tehrathum district, totaling 120 (54.2% women), with an age range of 30–68 years.

Gathering additional information on chili seed sources, crop geometry, seed rate, estimated seedling mortality rate, and fertilizer dose used the RRA. Since the database of chili is very general and missing in various aspects in the Nepalese context, RRA also complemented the desk review in this study. The 'Descriptor for Capsicum,' jointly developed by the International Plant Genetic Resources Institute (IPGRI), Rome; the Asian Vegetable Research and Development Center (AVRDC), Taiwan; and the Tropical Agricultural Research and Higher Education Center (CATIE), Costa Rica (1995) was used to study the phenotypic variations of available chili genetic resources in the locality, particularly flower color and orientation; fruit shape, size, color, and orientation; leaf size; maturity, and plant height. Different traits, classified according to the hedonic scales (1-9) mentioned in the descriptor, and the number of distinct varieties underwent evaluation.

The conduct of desk review collected data on chili variety, chili distribution and production, chili trade, import, and export. For this purpose, most of the data obtained came from the statistics of Nepalese agriculture published by the Ministry of Agriculture and Livestock Development in different fiscal years. Additional data on chili area and production recovery used FAOSTAT, an updated dataset maintained by the Statistics Division of the Food and Agriculture Organization of the United Nations. Since some important information appeared missing from published sources, assumptions were considered when calculating the per capita consumption of chili, with the estimation aided by the total domestic production and import data for chili in Nepal. An assumption pegged that 50% of the total imported quantity under the eight different Harmonized System (HS) codes were chili products. People between 15 and 64 years were considered chili consumers out of the total population of Nepal. Similarly, the calculation of the overall seed requirement for chili in Nepal proceeded according to the method published by the Alberta Government, Canada, under the open government program. During the RRA, the noted average crop geometry scored at 0.25 m^2 per plant, with 10% extra seedlings required to achieve the desired plant population per unit area. Based on the five-year data, the average thousand seed weights (TSW) of OPVs and hybrid chili calculation was 4.1 ± 0.08 g (n = 50) (SSSC, 2022). The total amount of chili seed required for the total area was estimated based on the calculated seeding rate per hectare (Alberta, 2018) as follows:

$$\text{Total seed required (kg)} = \text{Seeding rate}\left(\frac{\text{kg}}{\text{ha}}\right) \times (\text{total chili hectarage [ha]})$$

------- (i)

$$\text{Seeding rate}\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{\text{Desired plant population per sq. m} \times 1000 \text{ seed weight [g]}}{\text{Seedling survival rate} \times 100}$$

------- (ii)

$$\text{Seedling survival rate} = (\text{Germination rate [\%]} - \text{Seedling mortality [\%]}) / 100$$

------- (iii)

For the calculation, seed germination was set at 75% and the seedling mortality rate at 10%, as discussed during the field study. Consulting some experts in seed production and marketing also gained their views on seed production and the trade of chili in Nepal. All the data obtained from the field study and desk review proceeded with the analysis using MS Excel. Computation and comparison of mean values, and standard deviations, among others, transpired where meaningful.

RESULTS AND DISCUSSION

Genetic diversity and distribution of chili in Nepal

Chili distribution has a long history back to the 15th century when Christopher brought chili to Europe, and later in the 17th century, it entered Asia (Powis *et al*., 2013, Kraft *et al*., 2014). The introduction of chili to Nepal has non-existing documentation but could have been entered via India. Nepal is home to a wide range of chili genotypes. Three out of five capsicums, or about 60% of the recently identified cultivated species of *Capsicum* (Barboza *et al*., 2022), and some unidentified *Capsicum* species are under cultivation in Nepal. Some studies have discussed the northeast region of South Asia, including eastern Nepal, as a primary repository of chili biodiversity (Purkayastha *et al*., 2012; Rai *et al*., 2013, Jha and Saha, 2017). Some chili landraces, for instance, Akabare chili, have supposed to originate from the eastern mid-hills of Nepal. It might be due to the sympatric domestication (evolution of a new species from a surviving ancestral species while both species share the same geographic region) of chili genotypes in the particular ecology. Akabare chili is commonly grown commercially in Nepal, covering an area of approximately 1,481 ha throughout the country in 2021 (MoALD, 2022). The mode of pollination could have contributed to the genetic diversity of chili. A study reported a wider range (2%–91%) of outcrossing, with chili as suggested as a cross-pollinating crop species (Ritonga *et al*., 2018). Natural and artificial selection (variety development by breeder) can bring diversity to the chili gene pool (Shiragaki *et al*., 2022). Moreover, interspecific cross-compatibility between cultivated capsicum species (Barchenger *et al*., 2019) may have developed interspecific hybrids (Bosland and Baral, 2007), contributing to the genetic diversity. Some of the chili genotypes found in Nepal would have gone through the 'founder effect' that resulted in a new population, as reported by Baral and Bosland (2002).

The National Agriculture Genetic Resources Center (NAGRC) is the primary repository of available agricultural plant genetic resources (APGRs). A total of 11,236 APGRs conserved in the Gene bank consist of chili genetic resources with a share at approximately 0.96% (108 accessions) (Paudel and Joshi, 2018), with a total of eight Akabare chili landrace accessions currently conserved in the center. Akabare chili has emerged as a potential genetic resource with diverse distribution and wider adaptation (Jha *et al*., 2012, Karkee *et al*., 2022). It is becoming popular for its unique fragrance and spiciness, already cultivated in the mid and high hills of Nepal during the main season (April–December).

Nepalese chili genotypes have shown variation in qualitative and quantitative traits. Significant variation among chili genotypes emerged for the biochemical parameters like flavonoids, polyphenols, beta-carotene, and total carotenoid (Subedi *et al*., 2018). As for the morphological and agronomic traits, observed genetic diversity for the heat stress tolerance trait appeared in some Nepalese and exotic chili genotypes (Dahal *et al*., 2006). Akabare chili accessions showed a greater similarity to the *C. annuum* group, with

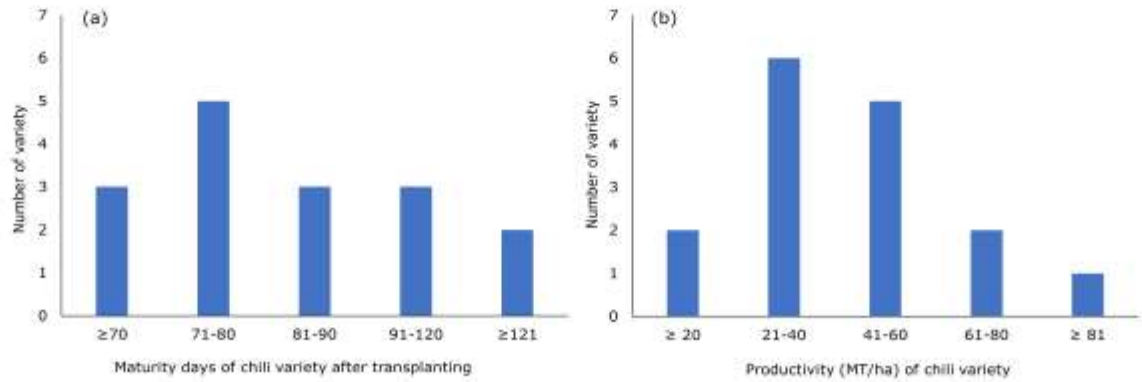

Figure 2. Graphical presentation of the total number of chili varieties listed (both released and registered) at Seed Quality Control Center, Ministry of Agriculture and Livestock Development of Nepal up to July 2021, and grouped according to (a) the maturity (first physiologically mature fruit ready for harvest) days after seedling transplantation; and (b) maximum yield potential (metric tons).

locations near the border between the *C. annuum* and *C. frutescens-chinense* groups (Nemoto *et al*., 2016). Akabare chili landraces demonstrated 25% variation for quantitative characters and approximately 22% for qualitative traits, suggesting a wide range of intra-varietal diversity (Karkee *et al*., 2022). A review work on genetic resource diversity, distribution, and uses of Akabare chili landraces in Nepal has also been published recently (Poudyal *et al*., 2023).

Trading of 16 commercial varieties of chili of different maturity and productivity inside the country exists (Figure 2a, b), with 81% as F1 hybrids (SQCC, 2021). 'Jwala,' a hot pepper, was the first chili variety released in 1994 for commercial distribution. After a long gap, successive registrations materialized for 12, one, and two varieties in 2010, 2012, and 2013, respectively. However, two chili varieties gained denotification, 'Sudra F1' registered in 2012 and 'Naina F1' in 2013, due to the discontinuity in import for more than three years. In 2019, two OPVs ('Fire Camp' and 'Hot Shot') gained recommendations for cultivation. About 50% of the registered varieties mature early (<80 days after transplanting), with 69% having a yield potential of 21–60 MT/ha. The released and registered varieties suited recommendations for Terai, river basin, mid-hill, and high-hill cultivation conditions in Nepal, which indicated the wider adaptability and distribution of chili genotypes in the country.

During RRA, recording the high variation between chili genotypes occurred in fruit shape, size, and orientation (mean value of distinctness 5 ± 1.5, n = 7), followed by floral characters (mean value 4 ± 0.8, n = 7). Fruit traits proved to be more easily identifiable and distinguishable for farmers than floral traits. Production districts nearer to the major cities (i.e., Dhankuta, Kathmandu, and Bhaktapur) showed higher variability of chili genotype than remote production districts, such as Dailekh and Tehrathum. The availability of chili varieties of farmers' interest in the market can address consumers' preferences for the fruit's shape, size, and hotness. Contrary to this, the Jhapa district showed the lowest variation (mean value 2 ± 0.5, n = 7) among the seven districts. It may be due to the tropical climatic conditions in Jhapa prevailing in the early monsoon that would have favored similar genotypes of early maturity. Among the seven districts studied, Dhankuta showed diverse phenotypic variations between chili genotypes, with a mean value of 5 ± 1.4. It could be due to the presence and cultivation of different varieties, including Akabare chili landraces in the district. Three levels of maturity— early, medium, and late— were mutual across the locations (Table 1). Farmers in Jhapa wanted to have early maturing varieties, whereas farmers in mid-hills like Dailekh preferred chili varieties that produce fruits for extended periods. The transplantation and harvesting time of chili in the districts studied showed that domestic production is mainly available from August to November (Figure 3).

The areas studied shared similar formal and informal methods of seed distribution. Seed companies, neighbors, and farm-saved seeds emerged as the principal sources. Of the total 120 respondents in RRA, 62% ± 3.2% (n

Table 1. Level of phenotypic variations observed in seven different chili-growing districts of Nepal during the Rapid Rural Appraisal (RRA) conducted in December 2020 and February 2021. The numbers under different five traits indicate the distinct types or levels of chili genotypes available in that particular district. Chili genotypes were categorized according to distinguishable morphological and agronomic traits that were discussed in the focus group discussions. Mean values ± s.d.

District	Major distinguishable morphological and agronomic characters					Average variation across districts ± s.d.
	Fruit shape, size, and orientation	Plant height	Flower color and orientation	Maturity	Leaf size	
Makawanpur	6	3	4	3	3	4 ± 1.2
Dailekh	5	4	3	2	3	3 ± 1
Dhankuta	7	4	5	3	4	5 ± 1.4
Jhapa	3	2	3	2	2	2 ± 0.5
Kathmandu	7	4	3	4	4	4 ± 1.4
Bhaktapur	6	3	3	4	3	4 ± 1.2
Tehrathum	4	3	4	3	3	3 ± 0.5
Average variation across traits ± s.d.	5 ± 1.5	3 ± 0.8	4 ± 0.8	3 ± 0.8	3 ± 0.7	4 ± 0.7

Figure 3. Graphical presentation of the chili seedling transplantation and harvesting month in the districts studied. Some of the landraces are perennial, with continuous harvesting for a long period within a year, but the harvesting time was averaged while preparing this chart. This crop calendar was prepared based on the farmers' feedback during the field studies in 2020 and 2021. Brown shades indicate the month of seedling transplantation, and green shades indicate the harvest time.

= 7) reached agrovets to buy seeds, 26% ± 3.9% used farm-saved seeds, and the rest 12% ± 1.1% shared with fellow farmers. Farmers in remote districts like Dailekh mostly used farm-saved seeds, whereas farmers near city/urban areas like Dhankuta, Jhapa, and Bhaktapur bought seeds from the seed market. The OPVs usually served as the farm-saved seed used, and agrovets supplied seeds of improved and hybrid varieties. Estimates revealed that the informal seed sector (farm-saved seed) supplies nearly half of the total seed demand, and the remaining 50% comes from the formal sector (local production and import). Of the total amount in the formal sector, imports met about 95% of the demand for chili seeds (DP Adhikari, personal communication, October 25, 2022). Meanwhile, based on the total area under cultivation, about 5,824 kg of chili seed (roughly 255 g/ha) reached the requirement in 2021.

Chili distribution, area coverage, production, and trade in Nepal

In 2020, Nepal contributed to the total chili area by 2.3%, 0.8%, and 0.6% in South Asia, Asia, and the world, respectively. Similarly, Nepal contributed to the total chili production by 6.9%, 0.6%, and 0.4% in South Asia, Asia, and the world, respectively (FAOSTAT, 2022). In Nepal, the area and chili production in the last four years (2018 to 2021) showed little ups and downs (Table 2). Chili was grown on approximately 20,576 ha of land with a productivity of 7.6 MT/ha in 2018, whereas in 2019, both area and production increased by 5% and 12%, respectively. However, a reduction in the chili hectarage by 5% transpired, with a slight change in production (-2%) in 2020. In 2021, a significant variation in hectarage (+13%) and chili production (+8%) appeared compared with 2020, with an average productivity of 8 MT/ha. The hectarage and production of Akabare chili increased by 53% and 28%, respectively, in 2021 compared to 2020. Recording of some gaps in national data took place, i.e., Akabare chili production was prominent in the Makawanpur district during field visits in 2021, but data for the same in the fiscal year 2020/2021 did not exist.

Chili production is diverse in terms of zones (Terai to high hills), variety (landraces to hybrids), and cultivation practices (subsistence to commercial), with productivity also varying greatly in producing districts. The Choropleth map of the district-wise distribution of the area and chili production in Nepal appears in Figure 4a, b. In 2021, the total area under chili production was 23,083 ha, producing about 184,885 MT of chili. Province One yielded the highest, contributing to national chili production by 30%, followed by Lumbini (22%) and Madhesh Pradesh (17%). The Gandaki Pradesh produced the least (3%) among the seven provinces. Of the 77 districts, the Morang district ranked the highest for both hectarage and production, contributing 13.56% to the national chili production. Following close were Kailali and Pyuthan in terms of production, contributing 7.8% and 6.3%, respectively, to the total chili production. Among the 77, Manang and Mustang, also known as districts beyond the Himalayas, contributed the least to the total national production (0.01%) (Data not shown).

Table 2. Total area, production, and productivity of chili in Nepal. The data combined the area coverage and production of both common chili and Akabare chili landraces (Data source: MoALD, 2022).

Year	Area, ha	Production, MT	Productivity, MT/ha
2018	20,576	155,383	7.6
2019	21,565	174,374	8.1
2020	20,439	170,653	8.3
2021	23,083	184,885	8.0

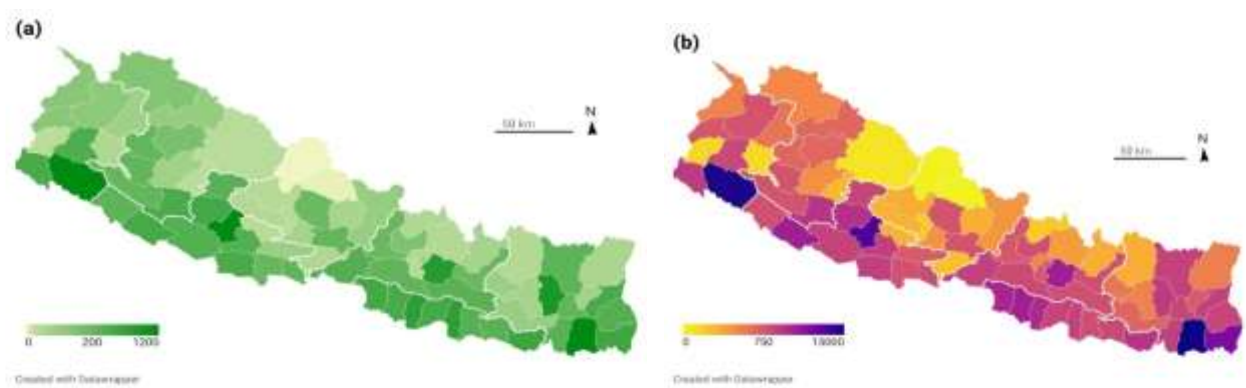

Figure 4. Choropleth map of Nepal showing the different color regions to visualize the district-wise distribution of (a) total chili cultivated area (ha) and (b) total chili production (MT) in 2021. The maps were developed using the data obtained from MoALD, 2022; and Datawrapper, an online software developed by Datawrapper GmbH, Germany.

The highest recorded chili productivity came from Lalitpur district (19 MT/ha), followed by Jhapa (15.7 MT/ha), Bara (13.2 MT/ha), Banke (12.4 MT/ha), and Morang (12.2 MT/ha). These were higher than the South Asian chili productivity (5.7 MT/ha), Asian productivity (10.4 MT/ha), and chili productivity of the world (10 MT/ha) in 2020 (FAOSTAT, 2022). The productivity of some remote and mountainous districts like Humla and Dolpa had less than 3 MT/ha. Despite remoteness and the prevailing warm temperate to temperate climates, the Mustang and Taplejung districts recorded quite good productivity (8–9 MT/ha). In contrast, road-accessible Terai and mid-hill districts, such as Mahottari and Dhading, showed very low chili productivity (3.8–4.2 MT/ha).

Nepal imports a considerable amount of chili and its products annually. Chili import-export-trading practice used eight different Harmonized System (HS) codes. It is difficult to differentiate between sweet and hot pepper chili products from HS codes and product names used in import. Therefore, the quantity described here combines both. Nepal imported 13,402 MT (equivalent to NPR 2,567 million or 19.75 million USD) of chili in 2021, 29% lower than in 2020. Export increased tremendously from 611 kg in 2020 to 2,360 kg (equivalent to NPR 7 million or 0.054 million USD) in 2021 (MoALD, 2022). However, the export volume (2.36 MT) was very negligible compared with the import volume (13,402 MT). The higher proportion of chili imports indicates an immense scope for national chili production and marketing to substitute imports. Furthermore, the increasing trend of per capita chili consumption assures the market potential of domestically produced chili. The estimated per capita chili consumption of 9.33 kg for 2020 increased slightly (+5.4%) in 2021.

Domestic and foreign markets are present for Nepali chili producers. The domestic market is outside the production districts, whereas the local market is within the district. About 88% of all respondents sold their produce to the market as commercial growers. The remaining 12% of the respondents consumed their produce with the inability to market. It could be due to less market information or other issues related to chili marketing. Across the seven districts, most commercial growers (65.8% ± 3%, n = 7) sold their produce in the domestic market, 17.5% ± 1.2% sold in the local market, and a few (5% ± 1.2%) exported to India. In the focus group discussion, about 2.7% of the respondents raised issues related to chili marketing, indicating the presence of a good chili market. The pickle industries, noodle factories, and fast-food companies in Nepal use chili in their products. Dried chilies are common in coloring foods and adding spiciness. Fresh chili is being traded on the market together with fresh vegetables, fish, and meat.

Issues of chili production and marketing in Nepal

Both biotic and abiotic factors are common challenges of chili production in Nepal. In this study, the respondents listed foremost issues with preference ranking the major concerns of chili production and marketing. Among the problems associated with chili production and marketing at the seven sites, 12 items, such as diseases, insects, slugs, birds, drought, heat, fertilizer, variety/seed, waterlogging, wind, technical knowledge, and marketing, revealed to be the major problems (Figure 5). Among the 12, five are biotic factors, five are abiotic, and two are related to management factors.

Biotic factors

The problems of biotic origin were dominant over abiotic, with a 49% ± 0.05% (n = 12) proportion. Among the five, the disease problem emerged as the main culprit of biotic origin. Across the seven locations, most farmers faced disease problems (16.4%), followed by insect pests (15.6%). Lack of suitable variety (seeds) shared 6.9%, followed by the problem due to birds, with a share of 6.2%. Slug infestation ranked the fifth problem, with a share of 3.5% of the total issues. Across the seven districts, Tehrathum was more vulnerable to biotic stresses, with 19% response accumulation across the seven locations. Dailekh (14.3%) and Makawanpur (14.7%) both ranked in the second position. Kathmandu (13%), Jhapa (13.4%), and Dhankuta (13.7%) showed a similar range. Bhaktapur ranked least by biotic factors, 11.8%. (Figure 5).

The disease problem came highest for Tehrathum (16%), followed by Jhapa (15%). The disease problem scored the lowest value for Dailekh (13%). Damping-off, dying-back, chili-leaf-curl-virus disease (ChiLCVD), anthracnose, root rot, cercospora leaf spot, powdery and downy mildew, bacterial and fungal wilt, and pepper veinal mottle virus comprise the general problems in chili production (Parisi *et al*., 2020). Among chili

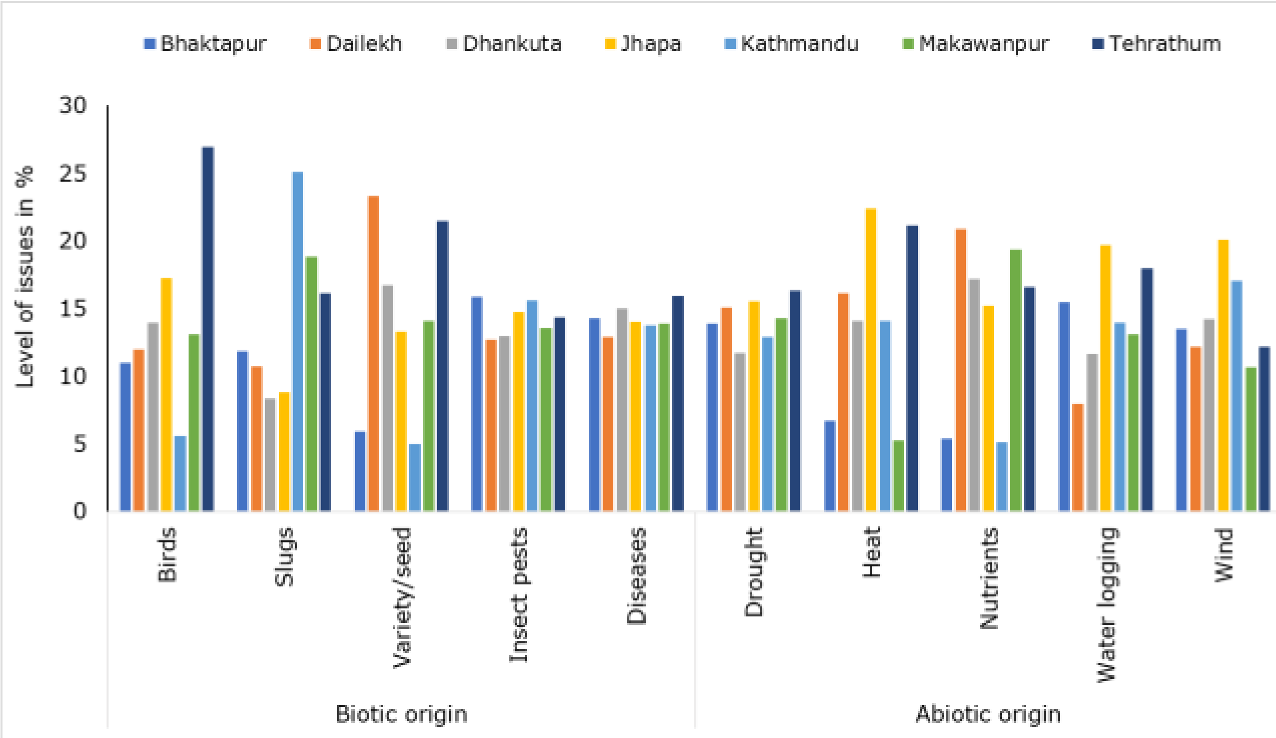

Figure 5. The bar diagram shows the level of chili production and marketing issues in percentage. Total responses on specific issues from 120 respondents across the seven districts during the field study in 2020 and 2021 were recorded and finally expressed in percentage ([total responses/120] × 100). The grey line in the middle of the X-axis separates the issues by their nature of origin.

diseases, ChiLCVD appears as one of the chief emerging problems (Barchenger *et al.*, 2019). Diseases, such as powdery and downy mildew, bacterial wilt, pepper veinal mottle virus, and leaf curl virus, have been reported from the field study.

The insect pest showed to be more problematic in the chili fields of Kathmandu (15.6%) and Bhaktapur (15.9%), followed by Dhankuta (14.8%) and Tehrathum (14.4%). The insects listed during the RRA were thrips, whiteflies, aphids, cutworms, pod borers, mites, pepper maggots, and nematodes. Farmers suffered difficulties controlling the thrips and faced losses at the economic level. In agreement with this, Parisi *et al*. (2020) reported up to 50% losses in chili production due to thrips. Slug infestation was found location-specific. Four farmers out of 120 respondents indicated that slugs were the main problem in chili fields, particularly at higher elevations. Across the locations, the highest number of respondents from Kathmandu (25%) reported the slug problem in the chili field. Slugs can climb up to 1.8 ± 0.5 m (n = 12) of the plant and damage the fruits. Birds highly hamper chili production in Tehrathum (27%), followed by Dhankuta (17.3%). Across the seven studied sites, the bird's problem ranked lowest in Kathmandu (5.6%). Birds, such as bulbul, mynah, parrot, crow, and grey treepie proved problematic in the chili field surrounded by trees and far from the farmhouse. Seven farmers of 120 reported birds as a significant problem in the chili fields.

A total of eight of 120 respondents reported problems associated with chili variety. A higher number of farmers from Dailekh (23.3%), followed by Tehrathum (21.5%), complained about the lack of suitable chili varieties in their localities. Study sites near the market center, such as Kathmandu and Bhaktapur, showed lower responses to lack of variety, 5%, and 5.9%, respectively. It could be due to the unavailable modern cultivars in the study areas located remotely from market access. Only 16 varieties listed in the National Seed Board of Nepal existed for commercial distribution, with no tolerant varieties recommended for a specific disease problem. A report states genotype roles ranked as the most crucial factor in improved yield (Parisi *et al.*, 2020).

Abiotic factors

About 40% ± 0.04% (n = 12) of issues were identified as of abiotic origin limiting the chili production in the studied areas. Among the five major abiotic factors listed, drought stress emerged as the most problematic compared with others. From the named 12 issues, drought stress shared 14.8%, followed by nutrients (10.1%), heat stress and waterlogging (6.2%), and wind (3.1%). Across the seven sites, Dhankuta faced the highest level of abiotic stress problem in the chili field (18.6%), followed by Tehrathum (16.9%). The lowest level of response records was in Bhaktapur (11%). The highest level of drought stress came from Tehrathum (16.4%), followed by Dhankuta (15.6%) and Dailekh (15.1%), with the lowest value recorded from Jhapa (11.8%). Drought stress was more prominent from April to June. The lower volume of water in running streams and the reduction in winter and spring rainfall could be a factor in prolonging drought (Mandal, 2021).

Farmers showed much concern about the supply of fertilizers (nutrients), which was also an emerging issue in the districts studied. Twelve of 120 farmers across the seven studied sites complained about the short supply of required nutrients in chili cultivation. About 20.9% of farmers from Dailekh, 19.4% from Makawanpur, and 5.4% from Bhaktapur experienced a few stocks of fertilizers. An estimation indicated that a hectare of cultivated land in Nepal received 72.9 kg of urea, 45.6 kg DAP, and 4.2 kg muriate of potash (MoP) in 2021, quite low compared with the recommended dose for vegetables (109.6 kg urea, 108.7 kg DAP and 66.7 kg MoP per hectare) (AITC, 2022). A short supply of fertilizer would be another reason for the low productivity.

Interestingly, heat stress scored a mild value (6.1%), together with waterlogging problems. The heat stress varied significantly across the seven locations. It may be due to variations in the altitude of the sites studied, and the effect of heat would have less impact at higher altitudes. Both heat and waterlogging stresses revealed challenges in Dhankuta (22% and 19.8%, respectively), followed by Tehrathum (21.2% and 18%, respectively). Surprisingly, the heat stress problem was moderate in lower elevations, such as Jhapa (14.1%). The availability of a heat-tolerant variety in Jhapa could have contributed to minimizing the effects of thermal stress. Bhaktapur and Makawanpur reported very low levels of heat stress problems at 6.7% and 5.3%, respectively. Similarly, the least waterlogging problem appeared in Dailekh (8%). Chili fields might have the advantage of topography (inclined, slopey land in most of the studied sites) in all the research locations, resulting in a lesser waterlogging problem. About 3.1% of the respondents reported wind as a problem. The damage to chili crops due to wind was the highest in Dhankuta (20.1%), followed by Kathmandu (17.1%) and Jhapa (14.2%). During the discussion, higher stem lodging was noticed in the plots receiving high nitrogen doses and without staking. Unbalanced application of nutrients and chili cultivation under low light conditions would have contributed to the lodging.

Managerial factors

Besides biotic and abiotic factors, about 11% ± 0.04% of issues inclined more related to managerial aspects. The lack of technical know-how of modern chili cultivation practices and market problems hindered the growth of the chili business in the studied areas. Both factors are highly dependent on the management skill of farmers. About 8.5% of farmers requested training on chili cultivation and market management. Across the seven locations, the highest response to poor management came from Dailekh (24.8%) and the lowest for Bhaktapur (7.4%). Most farmers (22%) from remote districts, such as Dailekh, responded to the unavailable technical know-how of chili production compared with farmers from districts near urban areas, i.e., Bhaktapur (9.7%). It indicates that urban farmers know more about the modern practices of chili production or have access to agricultural extension services. Most farmers agreed on the existence of good market demand. The chili marketing problem shared only 2.7% of the 12 issues. Looking at the respondents, 14 farmers out of the 120 could not sell the chili. Lack of market information and marketing network comprised the main issues of chili marketing. About 88% of farmers revealed commercially engaged in chili marketing, and only 12% used chili for household purposes. Using their chili produce could refer to an inability to market or low production volumes or use in processed products due to the low price for fresh chili. Of 106 interviewed farmers, 17.5% sold the chili to the local market (in the district), 65.8% to the domestic market (outside the district), and about 5% were able to export to India.

An increasing trend of per capita consumption, diverse market, and interest in the food industry has indicated that chili could be a highly potential spice crop in Nepal. However, environmental factors of physical or chemical origin can influence the quality of chili production. In the context of global climate change, expected fluctuations of many environmental factors are inevitable; consequently, chili will increasingly experience abiotic stresses, such as drought, heat, waterlogging, and salinity, among others (Zhou *et al*., 2022). Unlike biotic factors, it is a challenge to manage and escape abiotic factors due to unpredictable climatic conditions (Rosenqvist *et al*., 2019). Apart from climate change, anthropogenic causes, such as deforestation, soil degradation, as well as, declining water quantity and quality, may also challenge the chili yield and productivity in Nepal. In RRA, chili growers shared their experiences with the negative effect of shade on fruit production and pungency. Drought stress during anthesis and fruit development could affect capsaicinoid accumulation and total fruit yield (Ananthan *et al*., 2018). Thermal stress and low soil moisture conditions could increase capsaicinoids (Ruiz-Lau *et al*., 2011, Kopta *et al*., 2020), but in the meantime, could hurt the level of the pungency of the fruit (Mahmood *et al*., 2021) and fruit yield (Zou and Zou, 2021). So, the balance between fruit quantity and quality is always a matter of discussion for improved chili harvest. Some proposed thematic areas appear in Table 3 for further research from the Nepal perspective. Furthermore, it would be worthwhile to include areas that were not considered during the study but were important from the perspective of chili economics and livelihoods. Only seven sites in seven districts were studied using RRA; a recommendation for detailed research of other chili-producing areas covering the whole value chain requires attention.

Table 3. Selected thematic areas, based on a review of the literature and gap analysis of Nepal's chili research and development, are recommended for further chili-related studies in Nepal.

Thematic area	Tools and methods	Recommended by
Chili plant growth and development	Cell proliferation, and expansion, leaf size, photosynthesis, gas exchange, cell membrane thermostability, aerial and radicular biomass, root-to-shoot ratio	Phimchan *et al*., 2012; Zdravković *et al*., 2013; Zamljen *et al*., 2020
Stress physiology and phenotyping in the early vegetative stage	Chlorophyll fluorescence (Fv/Fm), gas exchange, stress tolerance index, carbon assimilation, chlorophyll content, leaf area	Rosenqvist *et al*., 2019; Zhou *et al*., 2022
Biochemical composition in plants under stress conditions	Capsaicin content, ascorbic acid, proline, flavonoids, chlorophyll a and b, carotenoids, starch, total chlorophyll content, chlorogenic acid, and apigenin 8-C-hexoside levels on leaves	Bhaskara *et al*., 2015; Escalante-Magaña *et al*., 2019
Plant osmotic adjustment	The water content of the leaf, osmotic potential of the leaf, osmotic adjustments, osmolyte accumulations	Anjum *et al*., 2012; Poudyal *et al*., 2017
Sexual reproduction and seed traits	Pollen viability, pollen tube growth, pollen quality, seed size, germination capacity, seedling vigor	Erickson and Markhart, 2002; Driedonks *et al*., 2018
Fruit quality	Fruit shape, size, capsaicin content, ascorbic acid content	Gurung *et al*., 2012 2020; Jeeatid *et al*., 2018; Kopta *et al*., 2020
Genotype screening for abiotic stress tolerance	Heat injury index, wilting score, leaf heat damage percentage, stress susceptibility indexes, chlorophyll fluorescence	Poudyal *et al*., 2018; Zhou *et al*., 2020; Rajametov *et al*., 2021
Karyological study	Genome sequencing, DNA fingerprinting and profiling, chromosome number, etc. of local chili landraces	De Assis *et al*., 2020; Magdy and Ouyang, 2020

CONCLUSIONS

Nepal has inhabited diversified genetic resources for chili, with a broader distribution of chili-growing areas in the country. In addition to modern chili varieties, Nepalese farmers also use distinct landraces, such as Akabare chili. Given the historical presence and cultural values of chili in the Nepalese kitchen, the fresh and processing market increased over the years, and there exists a good market for chili within the country. Additionally, there are two large chili markets in the neighborhood that Nepal has to explore. Initially, an import substitution strategy would be good for the development of chili economics in the country. Farmers facing disease problems, the infestation of insect pests, prolonged drought, waterlogging, shortage of fertilizers, and lack of technical know-how at different severity levels need solutions. For improved chili economics, the issues of chili production and marketing also require addressing. Demand-led chili breeding is necessary to prepare the new variety for stressed-growing environments. The findings will help to understand the current status of chili genetic resource diversity and variability, production, and marketing in Nepal. However, more advanced studies need to focus on maximizing genetic gain, subduing the production hurdles, and exploiting the market potential of Nepalese chili.

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