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REVIEW ARTICLE

Prospects and Potential for Sustainable Food and Nutritional Security in North Western Himalayan Region

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Abstract

The North Western Himalayan (NWH) region is experiencing faster warming than the global average, accompanied by increased precipitation and extreme weather events. These changes significantly impact hydrology, agriculture, biodiversity, and human health, exacerbating food and nutrition insecurity, especially in high mountain areas. However, certain wild food plants (WFPs) contribute significantly in the gastronomic, social, economic and ecological arena of the culinary heritage of the local population of the high Himalayas. However, a wide range of traditional local crops, not only having high nutritional value but also more resilient under changing climatic conditions, are slowly vanishing from popular culture Besides this there, is a significant lack of research on the health benefits, chemical composition, and nutraceutical profiles of traditional Himalayan crops and other WFPs. Addressing these gaps is essential for understanding their potential contribution to food and nutrition security. In addition, traditional food systems, rich in nutritional and medicinal values, are also declining due to changing food habits, environmental degradation, and inadequate documentation of WFPs, leading to a loss of agrobiodiversity and resilience in the face of climate change. Thus, a better understanding of the intricate interplay between traditional food choices and climate resilience will provide a comprehensive framework for community participation, awareness, modern breeding techniques to develop climate-resilient crop varieties, and value-addition options for sustainable food production. To achieve sustainable food and nutrition security in the NWH region a comprehensive, multi-faceted approach is required that integrates various sectors and relies on scientific research.

Keywords: Agrobio diversity, Sustainable development goals, Traditional food, Traditional knowledge, Wild fruit plants

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Introduction

Food and nutritional security of the NWH region

Food and nutritional security are key factors for human existence and socio-economic development and critically depend on the flow and services from ecosystems (Bohra *et al.,* 2015). It is noted that approximately 690 million people worldwide suffer from hunger, underscoring the persistent issue of food insecurity (Liu *et al.,* 2022). Ensuring food and nutritional security to a burgeoning population without degrading natural resources remains a key challenge for both national and global agendas to achieve sustainable development goals (SDGs), particularly the 'Zero Hunger' objective (Fróna *et al.,* 2019). Three of the United Nations' SDGs are closely related to nutrition security. Sustainable management of natural resources is crucial for ensuring the long-term availability of food, especially in regions like South Asia, which faces challenges such as declining resources, biodiversity loss, changing climate, inadequate water supply, poor socio-economic conditions, and rapid urbanization and industrialization (Rehman *et al.,* 2024). These factors influence access to resources, nutritional knowledge, and the ability of communities to sustainably manage their food systems. National and international

initiatives play a crucial role in addressing food and nutritional security. These efforts aim to systematize the connections between various resources, manage trade-offs, and leverage synergies to enhance sustainability and resilience in food systems (Vargas *et al.,* 2023).

The Himalayan ecosystem, often called the "Third Pole" or the "Water Tower of Asia," is vital for sustaining the populations of South Asia. It provides essential resources such as freshwater—holding around 30% of the world's total glaciated mountain area and serving as the source of 10 major river basins. Additionally, it supports energy production, biodiversity, forest resources, food, medicinal plants, and various aquatic products, making it a critical natural system for the region (Scott *et al.,* 2019). The Himalayan region is incredibly biodiverse, hosting a vast array of flora and fauna. For instance, over 675 edible plant species and nearly 1,743 species of medicinal value are found in the Indian Himalayan region alone (Dhiman and Muthanarasimha, 2022). The rivers originating from the Himalayas, such as the Ganges and Indus River systems, are rich in fish biodiversity (Winiger *et al.,* 2005; Rasul, 2014). The Ganges alone supports around 265 species of fish. These fisheries are crucial for food security and livelihoods, with India ranking second globally in terms of inland fisheries production (Harikrishnan *et al.,* 2024). Thus, Himalayan headwaters and watersheds are vital resources for sustaining agriculture and food security in this region.

The North Western Himalayan (NWH) region faces significant challenges related to nutrition security and micronutrient deficiencies despite recent progress in increasing per capita calorie intake. Hilly and mountainous terrain and environmental, cultural and socio-economic factors also aggravate the problem of malnutrition (Rasul *et al.,* 2014). In India, mountain states have an 18% prevalence of undernourishment, slightly lower than the national average. Further, steep slopes and harsh conditions create physical isolation from mainstream economies, leading to low carrying capacity in terms of agriculture, inefficient utilization of natural resources, low education standards, and high maintenance and transport costs (Gomiero, 2016). Moreover, malnutrition compromises health, contributing to higher child mortality rates and poor overall health outcomes. Similarly, poor nutrition hampers socio-economic development, limiting educational attainment and productivity. Periodic food shortages and insufficient access to nutritious food, clean drinking water, sanitation and health services are common, particularly in the poorest groups and people of remote locations in these regions. These threatening levels of undernutrition, besides vulnerability to diseases, further limit labor and economic productivity (Molotoks *et al.,* 2021).

Understanding and managing the availability of resources such as water, energy, and agricultural land is complex due to the NWH region's diverse geography and ecology. The interdependencies between upstream and downstream areas in terms of resource flow and impacts on water availability and quality are not well understood to date (Kattel *et al.,* 2023). The degradation of headwaters and unsustainable use of natural resources are disrupting the ecological balance of the Himalayan region. A major challenge is the lack of proper incentives and international policies to support sustainable resource management and conservation. Additionally, existing institutional frameworks are often inadequate in addressing the complex issues faced by mountain communities. This not only threatens the livelihoods of these communities but also puts the energy, water, and food security of South Asia at risk (Tiwari and Joshi, 2012; Rasul, 2014). Mountain communities often bear the costs of conservation efforts without commensurate benefits due to a lack of strong institutional frameworks that recognize their rights and enable them to participate in decision-making processes related to conservation, exacerbating economic hardships (Gupta *et al.,* 2022). Immediate actions are required to protect and sustainably manage Himalayan ecosystems, focusing on preserving biodiversity, improving land and water management practices, and promoting climate-resilient agriculture (Rasul, 2014).

Developing a strong regional dimension in the North-Western Himalayan (NWH) region, considering its transboundary nature, presents significant opportunities to enhance food and nutritional security through coordinated efforts and strategic planning (Das and Mishra, 2023). Water stress due to climate change may further exacerbate the situation in the NWH region. Increased extraction of groundwater leads decline in per capita water availability in many parts of the NWH region and has severely constrained agriculture and economic growth of the region (Gupta and Deshpande, 2004). NWH conditions are conducive to agriculture due to its regulatory microclimate and a unique feature with respect to topography, climate and production system that create favorable conditions for agriculture, primarily due to its regulatory microclimate (Rukhsana *et al.,* 2021). During winter, the NWH region plays a crucial role in influencing the weather patterns over South Asia by blocking western storms and mitigating the impact of frigid arctic winds. In addition, the NWH region offers a prime location for agro-biodiversity, playing a critical role in ensuring food and nutritional security not only for South Asia but also beyond (Rasul, 2014). Despite its rich potential for agro-biodiversity and agricultural productivity, the NWH region faces significant challenges related to environmental degradation and unsustainable practices (Tiwari and Joshi, 2012; Pandit and Kumar, 2013).

Further, the NWH region faces multiple challenges that significantly impact agricultural production and

productivity, compounded by rapid socio-economic changes. Severe decline in traditional nutritious 'coarse' grain, wild vegetable, fruit species, and pulses with change in agro-diversity (replacement with high yielding 'fine' grain), monocropping are also affecting the local dietary diversity and eventually nutrition security (Rasul *et al.,* 2019). The changes observed in the NWH region, where there is high-calorie intake but low nutritional status, are influenced by several socio-economic factors, including the increasing availability and promotion of industrialized food products (Rasul *et al.,* 2014). These shifts reinforce the demand for agricultural labor, prompting local farmers, particularly the youth, to seek alternative sources of income outside agriculture. In addition, the degradation of forests, soil quality, and hydrological systems in the Himalayan watersheds has significantly increased their vulnerability to erosion, with far-reaching consequences for soil fertility, water availability, and overall environmental health. Thus, traditional agriculture and rural economic activities are essential for growth, poverty reduction and nutritional security among rural hill communities (Viana *et al.,* 2022). The study by Mallikharjuna *et al.* (2010) highlights several critical nutritional challenges prevalent in the Himalayan region, particularly focusing on dietary diversity, food group intake, and the prevalence of micronutrient deficiencies. Thus, overall consumption patterns heavily rely on staples such as grains (including roots and tubers), vegetables, and fruits that are locally cultivated (Joshi *et al.,* 2021).

This review explores the factors affecting food and nutritional security in the NWH region using an ecosystem perspective, focusing particularly on climate change, biodiversity, and traditional and wild food resources in these areas (Figure 1). This review aims to assess the food and nutrition status of the NWH region and the underlying causes of malnutrition in hill communities and identify options and strategies to improve nutritional security in this region. The current review is crucial for informing policy formulation by government and non-governmental agencies to foster partnerships and collaboration with local communities, civil society organizations, research institutions, and development partners in the NWH region.

Impact of climate change in agro-biodiversity and nutritional security of NWH region

The assertion made by previous researchers regarding anthropogenic climate change and its profound impact on global food and nutritional security underscores a critical concern for the 21st century (Singh *et al.,* 2023). As greenhouse gas concentrations increase in the atmosphere, temperatures at higher altitudes tend to rise more rapidly than at lower elevations, amplifying the warming effect (Thakur *et al.,* 2024). Assessing the physical and biological environment, particularly in the context of catastrophic trends and variations in rainfall and temperature patterns due to climate change, reveals profound implications for the social, economic, and overall well-being of regional inhabitants (Abbass *et al.,* 2022). Climate change is increasingly recognized as a global challenge that requires localized solutions, especially in vulnerable regions like the NWH regions of India, Afghanistan, Nepal, and the Baluchistan province of Pakistan (Haq *et al.,* 2024). Strengthening governance frameworks and promoting inclusive development policies can foster climate-resilient livelihoods and improve food and nutritional security in the NWH regions (Kapruwan *et al.,* 2024).

The Himalayan region, especially the North-Western Himalayas (NWH), faces a range of challenges that are worsened by climate change and socio-economic factors, directly affecting food security and nutrition (Das and Mishra, 2023). Rising temperatures disrupt crop growth cycles, reduce water availability, and impact livestock health, leading to lower agricultural productivity. Additionally, poor road networks and inadequate transportation infrastructure make it costly and difficult for farmers to access markets, further hindering agricultural development in the region (Rasul *et al.,* 2014; Rasul *et al.,* 2019). Weak healthcare infrastructure limits access to medical services, impacting the health and productivity of communities (Dhimal *et al.,* 2021). The challenges affecting food security and nutrition in the NWH region are indeed multi-faceted and interconnected, reflecting broader socio-economic and environmental issues (Sage, 2013).

Strengthening institutional links is crucial for empowering farmers in the NWH region to adopt technology and enhance their adaptive capacity to climate change and other

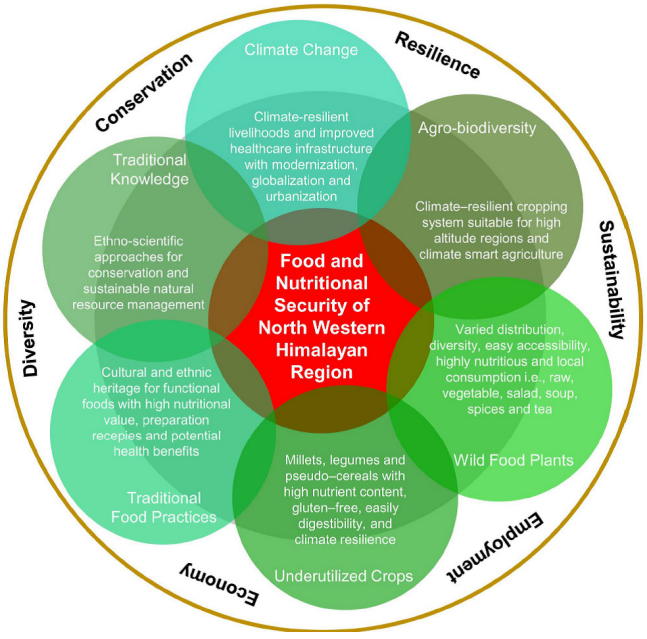

Figure 1: Schematic representation of various factors affecting the food and nutritional security of North Western Himalayan region

challenges (Mishra *et al.,* 2019). Therefore, achieving food and nutrition security in the NWH region is crucial for sustainable development, aligning with the global commitment under the Sustainable Development Goals (SDGs), especially for marginalized communities facing social, cultural, economic, and other forms of marginalization (Rasul *et al.,* 2019). Achieving food security in this region amid climate change challenges requires a comprehensive approach. This includes bridging knowledge gaps, encouraging youth participation in farming, promoting agricultural diversity, adopting gender-inclusive strategies, improving education, facilitating knowledge sharing, and integrating food security into broader policies aligned with the Sustainable Development Goals (SDGs) (Dhimal *et al.,* 2021). The Himalayan region indeed represents one of the world's richest biodiversity hotspots, encompassing a vast array of ecosystems and species diversity. However, this biodiversity is under significant threat due to various anthropogenic activities, land use change, invasive alien species and the impacts of climate change (Yadav *et al.,* 2021).

The mountainous ecosystems are much more delicate and harbor very rich biodiversity (Parihar *et al.,* 2021). Climate change poses significant threats to biodiversity, traditional medicine systems, food security, and human health in mountainous regions like the Himalayas, where inhabitants are primarily dependent on traditional medicinal practices. Changing climatic conditions weaken natural buffers and ecosystems, increasing the spread of invasive species and disease vectors, which significantly impact human health, food availability, and agriculture, particularly in mountainous regions like the Himalayas (Shrestha and Shrestha, 2019). Rising atmospheric CO_2 levels and their effects on food nutrition and ecosystem dynamics further highlight the urgency of addressing climate change. Strengthening biodiversity conservation while integrating climate adaptation and mitigation strategies is crucial to safeguarding both ecosystems and livelihoods (Dhimal *et al.,* 2021). Given the rapid decline in global biodiversity and the pressing impacts of climate change on agricultural production and food security, there is an urgent need to assess the current distribution and use patterns of wild food sources. This assessment is crucial for informing science-based policymaking aimed at conserving wild food diversity and associated traditional knowledge.

Reviving the forgotten food network of the NWH region

Today's global food and nutritional security is dependent on the performance of less than a dozen important crops (Gururani *et al.,* 2021). Major crops before the Green Revolution have now been reduced to the status of minor crops due to the adoption of input–responsive cultivars of major cereals to achieve food security (Meena *et al.,* 2021). This has reduced crop biodiversity, resulting in a potential threat to global food and nutritional security (Joshi *et al.,* 2021). However, nutritional security is more important than food security because undernutrition is intergenerational. In the existing situation, higher food production with ensured nutritional security is of prime concern (Parihar *et al.,* 2021). In the future, food and nutritional security will be at risk due to adverse climatic conditions. The impact of climate change is to be reflected more on small farmers of hilly regions due to a lack of livelihood opportunities. Under these circumstances, traditional hill crops such as millets, pseudo–cereals and some legumes (also known as nutri–cereals") are inherently rich in minerals, protein, vitamins and dietary fibers and intrinsically more resilient to abiotic and biotic stress as compared to largely accepted cereals and hence are best suited for climate–resilient cropping system in climate-smart agriculture (Kumar *et al.,* 2021).

Diversification and intensification of existing cereals-based cropping systems with legumes, millets and pseudocereals could be an effective and sustainable way to achieve food and nutritional security in the NWH region (Joshi *et al.,* 2018; Parihar *et al.,* 2021). The cultivated area of nutrient-dense crops such as millets, legumes and pseudo–cereals has been reduced in the last couple of decades, but these crops have regained popularity in recent years due to their high nutrient content, gluten-free, fibrous, protein-rich, non–acid forming high digestibility, wider adaptability and climate resilience (Joshi *et al.,* 2020). These crops are known as climate-smart crops, superfood crops and crops of the 21st century (Paschapur *et al.,* 2021; Parihar *et al.,* 2021). A wide range of flora is productively cultivated under natural environments owing to the presence of different agro-climatic zones in hilly topographies of NWH region. In this region of India, the major traditional food crops are millets and pseudocereals, which are considered potential crops because of their high nutrient content, low glycemic index and antioxidant properties (Kole *et al.,* 2015; Joshi *et al.,* 2018).

India is considered as a second spot for genetic diversity of finger millet and barnyard millet, which has higher fibre and iron content than rice and wheat, and is used for preparing traditional food such as "madira ki kheer" in Uttarakhand hills. Similarly, foxtail millet is and ancient domesticated annual staple food crop which holds second place in the global millet cropping area after pearl millet. Black soybean is traditionally cultivated as a remedial food in the NWH region with a capacity to survive under moisture stress but remain underutilized due to poor consumer acceptance (Pandey *et al.,* 2016; Parihar *et al.,* 2021). Horse gram is a neglected crop with high nutraceutical properties and is grown for food, medicine and fodder by resource-poor, rural and tribal communities of the NWH region (Cullis and Kunert, 2017; Aditya *et al.,* 2019). Rice bean is grown in a wide range of soils and is resistant to disease, pest, drought

and waterlogging stress. Buckwheat is the best-suited functional food for contingent crop planning under aberrant weather in the NWH region due to its short lifecycle, lower seed-to-seed maturity, small leaf area, deep root system and drought tolerance. Grain amaranth and Quinoa are emerging pseudo–cereals and have been gaining attention recently in the NWH region due to their higher nutraceutical properties, leafy vegetable, and fodder (Ruiz *et al.,* 2016; Parihar *et al.,* 2021).

Additionally, crop diversification (termed as 'Barahnaja system' in Uttarakhand) has been now recognized as a prime way for making agricultural systems sustainable and is one of the most cost-effective, ecologically feasible and rational ways of reducing agricultural uncertainties, especially among small–scale farmers (Gururani *et al.,* 2021). Amid changes in taste and preferences of people, growing per capita income and high demand for nutritional food products, crop diversification has a huge role to play in the NWH region. This system is to meet nutritional security since different crops are cultivated which can provide diverse nutritional supplements (Parihar *et al.,* 2021). Although potentially or underutilized crops, these have tremendous potential to support smallholder farmers and rural villagers by improving their economies besides food and nutritional security during a distressed environment. Sustainability and reliability of various models are required for the promotion and encouraging startup entrepreneurs for income generation through value addition of millets and pseudocereals.

Enhancing staple and potential crops to increase their vital nutritional content is a strategy to tackle the malnutrition challenge of the NWH region. Conventional plant breeding, on the other hand, can no longer meet the ever-increasing global and national food as well as nutritive requests due to certain drawbacks such as linkage drag and the impact of the environment on the trait of interest (Parihar *et al.,* 2021). Various current strategies employing for genetic enhancement of crop plants for improved nutritional values include conventional breeding methods such as gene transfer among related species through hybridization; the bio–fortification of crops, particularly for micronutrients; recently developed molecular breeding and transgenic approaches, which offer the most rapid way to improve nutritional status or flavor, as well as to eliminate bitterness and anti-nutritional elements to develop high–nutrient commercial cultivars among major cereals as well as potential crops for NWH region (Joshi *et al.,* 2009; Irfan and Dutta, 2017). In addition, the utilization of microbes to foster the uptake and translocation of nutrients is a promising option and may be integrated with agronomic or breeding bio-fortification approaches. Plant growth–promoting soil microorganisms improve nutrient mobility from soil to economic plant parts and hence contribute to nutritional security (Parihar *et al.,* 2021).

Wild food plants of the NWH region

The Himalayan forests hold profound ecological, social and culinary significance, playing a pivotal role in supporting the livelihoods and cultures of remote indigenous populations (Abbas *et al.,* 2021; Haq *et al.,* 2024). In the tribal region of the NWH region, several factors contribute to food insecurity and poverty among local communities, including man-made catastrophes, rapid population growth, local livelihood strategies and limited food accessibility. Wild food plants (WFP) are non-cultivated plant species that local communities gather or harvest from natural ecosystems for various uses within their food systems (Sharma *et al*., 2024). These plants, which include herbs, trees, shrubs, and climbers, play a crucial role in supporting food security, nutrition, and medicinal practices in these regions (Borelli *et al.,* 2020; Harisha *et al.,* 2021). Wild food plants (WFPs) indeed hold significant potential to alleviate micronutrient deficiencies, especially in Indigenous and rural communities (Pawera *et al.,* 2020). NWH region is diverse, being composed of plateaus, side valleys, high mountains, forests, pastures, and cultivated fields providing varied habitats for different kinds of wild vegetables and fruits. However, the distribution, diversity, and consumption of WFPs vary significantly across different regions due to several factors such as availability, cultural knowledge, nutritional importance, and climatic conditions. Local communities know the proper time, method and most suitable seasons for collection or in terms of the nutritional value of wild vegetables using traditional knowledge and are usually cooked in traditional tribal styles (Aziz *et al.,* 2020).

Primarily consumed WFPs in NWH region are in the form of vegetables (i.e., *Nasturtium officinale, Cardamine hirsute, Berberis aristata, Amaranthus viridis, Allium humile, Dryopteris stewartii, Trichosanthes cucumerina, Prunus armeniaca, Solanum nigrum* and *Phylanthus emblica*), leaves (i.e., *Rheum species, Taraxacum officinale, Viola odorata, Plantago species, Phytolacca acinosa, Oxyria digyna, Oxalis corniculata, Medicago polymorpha* and *Malva neglecta*), raw/ dried fruits (i.e., *Rubus ellipticus, Prunus armeniaca, Rubus species, Fragaria nubicola, Ficus carica, Berberis lyceum, Vitis jacquemontii, Ziziphus jujube, Zanthoxylum armatum, Pyrus pashia, Punica granatum* and *Hippophae rhamnoides*), spices and flavouring agents (*Nepeta floccose, Micromeria biflora, Sesamum orientale and Mentha arvensis*), salad or soup (*Stellaria media, Malva neglecta, Taraxacu mofficinale, Urtica hyperborea* and *Thymus linearis*), and mushrooms (*Geopora arenicola, Morchella vulgaris, Morchella esculenta* and *Flammulina velutipes*) (Abdullah *et al.,* 2021). A few species were used as tea substitutes, such as *Thymus linearis, Taxus wallichiana, Geranium pratense, Fragaria nubicola, Bistorta amplexicaule, Bergenia ciliata, Abies pindrow, Rheum webbianum, Acorus calamus, Cichorium intybus,* and *Origanum vulgare* (Haq *et al.,* 2022; 2024). It's fascinating

to note the seasonal availability of WFPs in the Himalayan region, influenced by cold temperatures during the winter months. Few vegetable species can be propagated for upto 9 months, whereas few fruit species, such as *Zizphus* species, *Ficus, Morrus*, *Vitis jacquamontiana, Punica granatum,* and *Sideroxylon mascatense* are only available for a few months. These WFPs are vital sources to most households in high altitudes of NWH, as they were unable to produce food because of unfavorable weather patterns in this region (Ding *et al.,* 2021).

It is interesting to note how WFPs are utilized by tribal people and shepherd communities in the valleys and foothills of the Himalayan region. They are partially or completely dependent on WFPs, which primarily belong to Amaranthaceae, Leguminosae, Rhamnaceae, Rosaceae, Lamiaceae, Polygonaceae, Brassicaceae and Moraceae. The most dominant WFP categories based on their uses included vegetables, fruits, chutneys and sauces and raw food species (Abdullah *et al.,* 2021). Enlisting WFPs as "functional foods" highlights their recognized nutritional value and potential health benefits beyond basic nutrition (Abdullah *et al.,* 2021). As reported earlier, WFPs indeed offer a wealth of nutritional benefits and potential socio-economic advantages, specifically in poor traditional communities of the NWH region (Abdullah *et al.,* 2021). The limited research that has been done on wild vegetables and fruits consumed in the food systems of the NWH region underscores several gaps and opportunities for further exploration and understanding (Pawera *et al.,* 2020). Climate variations across different altitudes significantly influence the practice of consuming WFPs in the NWH region. While historically important for local diets and cultural practices, the consumption of WFPs has declined in recent times due to factors like modernization, globalization, and urbanization. This shift in dietary habits has led to a reduction in the gathering and consumption of WFPs, contributing to a decline in the populations of some plant species (Haq *et al.,* 2024).

Moreover, the consumption of WFPs, such as wild vegetables, mixed with other foods, has been a tradition across human societies throughout history (Pawera *et al.,* 2020). Several recorded wild edibles in various regions are indeed becoming an income resource for local populations. This economic aspect adds another layer of significance to the utilization and conservation of WFPs (Singha *et al.,* 2020). Traditional plant foraging plays a crucial role in the sustainability of food systems in marginal tribal areas and contributes significantly to the improvement of regional cuisines. Thus, documenting the vast repository of ecological and plant knowledge in collaboration with indigenous societies is urgently necessary (Sahana Florence and Mishra, 2024). Conducting gastronomical field surveys can indeed be an effective strategy to document and preserve traditional plant foraging practices and culinary knowledge (Soukand *et al.,* 2020). Collaborative efforts involving various stakeholders such as the government, food scientists, ecologists, social activists, agriculturists and local tribes are crucial for achieving SDGs related to food sovereignty and food security in the NWH region (Charoenratana *et al.,* 2021). Research and development activities dedicated to WFPs hold significant potential to address contemporary challenges such as food security, biodiversity loss, and cultural preservation (Semwal *et al.,* 2022). Further, it will be suitable to inspire scholars, pharmaceuticals, and other organizations to develop a plan for properly managing and exploiting these highly valuable wild edible fruits.

Traditional food and foraging practices among native populations of NWH region

The major cause of malnutrition in the NWH region is to lack of sufficiency of fresh fruits, grains, meat, legumes, vegetables, and milk (Ojha *et al.,* 2022). This deficiency often stems from various socioeconomic factors, limited agricultural productivity, and challenges related to the accessibility and availability of diverse food sources. However, the region also benefits from traditional crops and food preparation systems that have sustained the community's dates back and still continue to play a crucial role in meeting nutritional requirements (Adhikari *et al.,* 2019). The summer meadows of the NWH region serve as crucial reservoirs for a variety of important food and medicinal plant species. These meadows, often located at higher altitudes, are characterized by diverse flora adapted to the alpine and subalpine environments (Khan *et al.,* 2024). People with limited income often turn to wild food species for several reasons, including their accessibility, nutritional value, and abundance (Bisht *et al.,* 2018). However, the naturally gifted species of WFPs face several threats that endanger their sustainability and availability. Climate change indeed poses challenges to food production by altering the suitability of land for agriculture and affecting the distribution of wild food resources. Ancient cultural practices related to utilizing wild flora and fauna in the NWH region are indeed recognized for their significance among local inhabitants, particularly those residing in higher altitudes (Khoury *et al.,* 2016).

The ethnic groups of the NWH region have a strong cultural belief that wild plants are rich in essential micronutrients, minerals and vitamins (Ojha *et al.,* 2022). The presence of traditional knowledge (TK) and ethno-scientific approaches is fundamental for conservation and sustainable natural resource management, especially in the context of developing sustainable food systems and supporting survival during periods of food insecurity like famine (Haq *et al*., 2022). Traditional wild food knowledge encompasses a rich tapestry of practices deeply intertwined with local biodiversity and socio-cultural contexts (Das, 2024). Traditional food systems are deeply rooted in cultural practices and local

environments, encompassing a diverse array of food plants, wild edibles, and culinary traditions that have evolved over generations. Traditional food systems are considered valuable in terms of providing lower calories and Vitamin A, zinc, calcium, iron, and saturated fat, thus having high nutritional energy value (Ojha *et al.,* 2022). Indeed, traditional food systems possess several characteristics that contribute significantly to food supply and environmental sustainability (CINE, 2021). Traditional knowledge systems often recognize the dual role of food as both nourishment and medicine. Certain foods and herbs are intentionally incorporated into daily diets to prevent and treat ailments, promoting overall health and longevity (CINE, 2021). Thus, traditional food and dietary structures play a crucial role in promoting sustainable development across several dimensions, including farming, food safety, and poverty mitigation (Joshi *et al.,* 2015). Therefore, supporting the multiplicity of foods and species consumed in indigenous regimes holds substantial profits from both sustainable food structures as well as public health perceptions (Pandey *et al.,* 2023).

The cultural and biological heritage associated with traditional food systems have been neglected and underutilized over the past decades and indigenous communities representing the knowledge reservoir of endangered plant species need immediate documentation (Swiderska *et al.,* 2022). However, recently, they became the center of attraction of research with a focus on battling for food sustainability and healthcare systems in far-flung tribal regions and the advancement of unique local cuisines. The use of plants and food recipes in rural household treatment systems is indeed a fundamental aspect rooted in local communities' deep knowledge of natural resources and their medicinal properties. Local communities often possess profound knowledge about the medicinal properties of food crops, understanding their efficacy in treating numerous ailments and infections (Ojha *et al.,* 2022). This awareness is rooted in centuries-old practices and empirical observations passed down through generations. Therefore, these traditional and WFPs perform diverse functions besides food and nutritional security, such as immunity boosting, therapeutic remedies, and repair of cellular damage to wound healing and ailments, thus acting as protective defenses against diverse sicknesses (Martin *et al.,* 2016). TK plays a crucial role in rediscovering and revitalizing traditional ingredients, including orphan crops and wild crop relatives, which are valuable in combating food insecurity and preserving bio-cultural food traditions in the NWH region. Women's integral role as custodians of TK about nutritional facets of medicinal and eatable species is crucial in many communities, including those in the NWH region (Ojha *et al.,* 2022). The community's management of natural resources in the North-Western Himalayas and similar regions, is indeed critical for sustaining local food systems and diets. Ethnobiological studies are indeed crucial in the process of food scouting within indigenous communities (Haq *et al.,* 2022; Bhartiya *et al*., 2025). This clearly imitates that the innate nutritional pattern prevalent in marginal hill communities fulfills diverse nutritional requirements and is perceived as a healthy food system by a significant portion of the population.

Low transmission of TK among youth and fluctuating food practices are indeed significant factors contributing to the loss of traditional and valuable information amongst native populations. The shift in ethnic, communal, and spiritual values indeed poses a significant threat to traditional food systems (Das and Mishra, 2022). The migration of the younger generation from rural areas to towns and cities in search of white-collar jobs has significant implications on traditional agricultural practices, food systems, and nutrition supply in the NWH region (Pingali, 2015). The involvement of researchers in transforming traditional knowledge into scientifically proven conclusions is crucial for identifying and promoting underutilized plant species with high nutritional value, especially those resilient to changing climatic conditions (Khan *et al.,* 2024). Hence, switching to locally found wild edible foods can indeed play a significant role in addressing the challenges posed by climate change, food insecurity, and population growth (Haq *et al.,* 2022). Utilizing wild plant species in agroforestry systems can indeed offer various competitive advantages over modern agriculture systems (Ollinaho and Kröger, 2021). Protecting native food systems and diets to ensure they continue to maintain food, nutrition, and health benefits requires a holistic and realistic approach.

Conclusion and way forward

The Himalayan region plays a crucial role in sustaining over 1.6 billion people, making its ecological conservation and sustainable resource management imperative. Integrated approaches to managing farmlands, forests, watersheds, and rangelands are essential to addressing food and nutritional security challenges, while ensuring long-term environmental stability. Enhancing resource efficiency, reducing climate vulnerability, and harmonizing policies across sectors will be key to sustaining water, energy, and food systems. Addressing malnutrition in rural hill communities requires targeted interventions, such as promoting climate-resilient crops, improving dietary diversity, and strengthening local food systems. The North-Western Himalayas (NWH) are facing rapid climatic changes, leading to shifts in food systems, declining agrobiodiversity, and increased risks to traditional farming communities. Farmers in this region are highly vulnerable to climate-related disruptions, necessitating adaptive strategies. WFPs, which have been integral to traditional diets and medicinal practices, are now under threat due to climate change and

overexploitation. However, their potential for improving nutritional security and livelihoods remains untapped. Successful interventions, such as the promotion of millets under India's National Food Security Mission (NFSM) and Sikkim's organic farming model, demonstrate how policy support and community participation can revitalize traditional crops.

Similar approaches, including incentives for cultivating underutilized crops like amaranth, seabuckthorn, and buckwheat, should be expanded in NWH states like Himachal Pradesh and Uttarakhand. To safeguard food diversity and strengthen local economies, efforts must focus on value addition, improved processing technologies, and market integration. Establishing Geographical Indications (GI) for indigenous crops, linking farmers to sustainable agri-business models, and expanding government-backed initiatives for traditional crops will ensure economic viability. Additionally, leveraging agroforestry and mixed cropping systems, as practiced successfully in Nepal's mountain farming communities, can enhance resilience against climate stress.

Future research should focus on genomic and metabolomic studies of climate-resilient crops, the biofortification of WFPs, and development of stress-tolerant crop varieties through advanced breeding techniques. Policies must integrate food fortification, micronutrient supplementation, and climate-smart agriculture to enhance nutritional outcomes. Awareness campaigns and farmer training programs will be crucial in bridging the gap between scientific advancements and traditional knowledge. A comprehensive strategy combining scientific research, policy interventions, and community-driven conservation is essential for improving food security and sustaining Himalayan biodiversity. By adopting a multi-pronged approach, the region can move toward self-reliance (AtmaNirbhar Bharat) while contributing to global sustainability goals.

Author Contributions statement

The idea of the study was conceptualized and designed by S.K.Y., A.K. and R.J. drafted the manuscript, and S.K.Y. edited and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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