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Status, Perspectives and Constraints of Temperate Vegetable Production in Himachal Pradesh

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Abstract

In Himachal Pradesh, cultivation of temperate vegetables has evolved from subsistence farming to a commercialised, technologically integrated industry that provides a significant component of the state's agricultural economy, as well as a significant share of the country's vegetable supply. The diverse altitudinal zones, from subtropical low hills to dry temperate trans-Himalayan regions, create specific microclimatic conditions that enable off-season vegetable production and the cultivation of high-quality vegetables in Himachal Pradesh. Vegetable production has expanded significantly in area and productivity in the last decades owing to varietal improvement, protected cultivation, micro-irrigation and integration of pest management interventions. The sector creates substantial rural employment, promotes nutritional security, and contributes largely to the state's Gross Domestic Product. Sustainability in the production of temperate vegetable crops can further be enhanced by addressing emerging challenges such as climate variability, evolving water resource dynamics, increased technology adoption at the farm level, better infrastructure, greater refinement of market operations, as well as reduced post-harvest losses. Strengthening farmer-market linkages through clusters, value chain integration, FPOs, precision farming, protected cultivation, as well as climate-resilient varieties is essential for risk mitigation and productivity enhancement. Despite being highly competitive in national markets, export potential has largely been underutilised owing to infrastructural constraints. Therefore, an innovation-led, climate-smart and value chain-oriented approach will be essential to enable Himachal Pradesh to turn into a model region for sustainable temperate vegetable horticulture in mountainous ecosystems.

Keywords: Climate-smart agriculture, Himachal Pradesh, Protected cultivation, Off-season, Vegetable production, Temperate vegetables, Value chain integration

Himachal Pradesh is situated in the north-western Himalayas, encompassing an area of 55,673 km² with elevation varying from 350 metres in the Shivalik foothills to 6,975 m in the high Himalayas. The state offers exceptional advantages for temperate vegetables cultivation owing to its diverse altitudinal gradients and agroclimatic conditions (Moharana *et al.* 2023). Himachal Pradesh encompasses four distinct agro-climatic zones that support the cultivation of different vegetable crops throughout the year. The state's climate is illustrated by distinct, notable seasonal patterns with monsoon rainfall accounting for 70-80% of annual precipitation, varying from 1000-2500 mm subject to altitude and orientation (Anonymous 2023d). Temperature fluctuations are pronounced throughout altitudinal zones, with mean annual temperatures ranging from 24°C in the foothills to sub-zero temperatures in high-altitude regions during winter months (Yadav *et al.* 2021). These climatic conditions confer inherent advantages for generating high-quality produce during periods when plains endure extreme temperatures, enabling farmers to secure premium prices in national marketplaces (Barwal & Sharma 2023).

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Agriculture serves as the backbone of Himachal Pradesh's economy, contributing substantially to the state's income, food security and socio-economic stability. The change in subsistence agriculture to commercial horticulture in the state was initiated during the years after Independence, when the policies by the state were very active in promoting horticulture as a development strategy to help the hill communities in their growth and development (Kumar *et al.* 2025). In this varied agricultural environment, the cultivation of vegetables, particularly temperate vegetables, has become notably prominent (Singh *et al.* 2025b). Currently, vegetable production occupies over 87,485 hectares, which generates over 1.8 million tonnes each year and significantly increases household incomes and state revenues (Anonymous 2022-23). The state has gained a reputation for being a leading vegetable growing area in northern India and has continued to serve the markets in Punjab, Haryana, Chandigarh and Delhi. In comparison to monocultures of wheat and rice in the rest of the adjacent plains, the agricultural system of Himachal Pradesh is more focused on crop diversification, thus resulting in greater land-use efficiency and increased resilience to climatic and market changes (Gummagolmath *et al.* 2020). The cropping patterns of the mid and high hill districts are mostly determined by the green peas, French beans, cauliflower, cabbage, carrot, tomato and capsicum, which are the key crops of the state. The green peas especially have become a flagship cash crop, and they are widely grown in Shimla, Solan, Kullu, Lahaul and Mandi (Rana *et al.* 2023). The supply of temperate vegetables contributes significantly to the off-season supply, and this allows Himachal Pradesh to meet the demand deficit in the plains when production is low (Sharma & Shandil 2021).

Cultivation of temperate vegetables has now advanced into a multi-dimensional agricultural business involving economic, social and environmental aspects of rural development. The industry is not just limited to primary production but also to the seed production, processing, marketing and exporting, which are all involved in enhancing the economic growth of the state and the rural employment. Himachal Pradesh is receiving about ₹3,500-4,000 crores of the economy of the state every year through the temperate vegetable sector, representing 8-12% of the Gross Domestic Product of the state (Anonymous 2024b). Temperate vegetable cultivation in Himachal Pradesh possesses significant future potential. Therefore, the present review aims to examine the status, growth potential, production constraints and opportunities for temperate vegetables cultivation, particularly in Himachal Pradesh, emphasising the importance of agro-climatic conditions, diversity, technological interventions, economic and social importance of cultivating temperate vegetables in Himachal Pradesh.

Agro-Climatic Zones and Geographic Distribution

The topography and geography of Himachal Pradesh exerted a significant effect on the temperate vegetables growing environment by having a distinct altitudinal gradient, multifaceted terrain and very heterogeneous microclimatic regimes. This creates an assortment of agro-ecological niches, thus allowing the vegetable crops to be diversified and unique farming systems to be designed (Barwal & Sharma 2023). The state is divided into four major agro-climatic zones which differ as a result of variations in altitude, temperature, precipitation and soil characteristics (Figure 1).

Sub-Montane and Low Hills (240-1000 m asl) region includes the lower regions of Kangra, Una, Hamirpur and some parts of Bilaspur. It includes less than 15 per cent of the state's area. It has a sub-tropical climate with an average annual temperature of 15-23°C and an annual precipitation of 1000-1500 mm (Barwal & Sharma 2023). The alluvial and colluvial soils are the most common and have good drainage and moderate fertility (Nazir *et al.* 2021). Tomato, capsicum, peas and beans can be grown between October and April when extreme temperatures limit this in the plains (Soni *et al.* 2016). This prolonged period of growth serves the sequential production of two to three vegetable crops in a year with effective crop and variety planning (Barwal & Sharma 2023). The Mid-Hill Temperate (1000-2000m amsl) region is the main zone of growing the vegetable produce, and it covers Shimla, Solan, Kullu, Mandi and some portion of Kangra, encompassing approximately 45 per cent of the state. It has sub-humid temperate climates with yearly temperatures of 12-18°C and precipitation of 1200-2000 mm (Singh *et al.* 2022). The key crops here are potato, cabbage, cauliflower, beans, peas and other

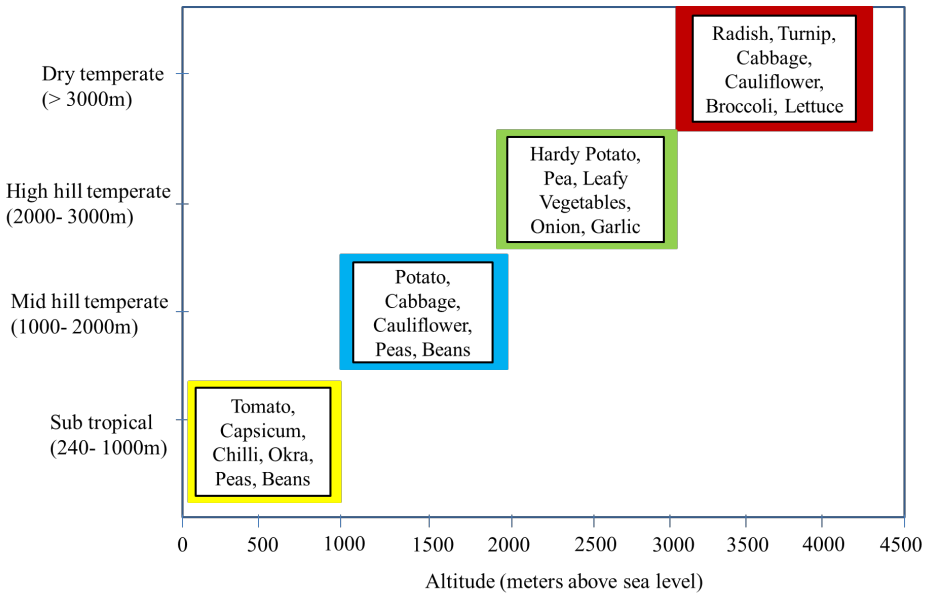


Figure 1. Agro-climatic zone distribution showing geographic area and production patterns across different elevation zones in Himachal Pradesh

root vegetables. The high hill temperate (2000-3000 m amsl) zone is characterised by cool temperate weather, covering about 25 per cent of the state. The region experiences an average annual temperature of 6-12°C and precipitation of 800-1500mm, including winter snow. The area has a short growing season (May-September) where potatoes, peas, leafy vegetables, onions and garlic are grown, and there is an absolute need to manage the varieties and inputs (Barwal & Sharma 2023). This region is a seed production centre for vegetables. Dry temperate and Trans-Himalayan (above 3000 m asl) constitute the cold arid region with Lahaul and Spiti, higher parts of Kinnaur and other high-altitude regions forming the major parts of this zone and covering about 15 per cent of Himachal Pradesh. The climate of the region is characterised by an average temperature of less than 6°C per year, with low precipitation of 200-600 mm/year (Rana *et al.* 2018). Crops like radish, turnip, cabbage, cauliflower, broccoli, lettuce and native leafy vegetables are resilient crops for this region (June-August).

STATUS OF VEGETABLE PRODUCTION IN HIMACHAL PRADESH

The state has experienced significant agricultural transformation during the past five decades and has become an eminent temperate vegetable producer in India due to its agro-climatic advantages, infrastructural development and market-oriented cultivation policies (Singh & Chauhan 2018). Furthermore, the rise of an urban middle-class market, with its unique culinary preferences and a higher level of health concerns, created a growing demand for high-quality vegetables. Lowland areas especially prefer temperate vegetables that are grown in hills since they have a unique taste, freshness, sweetness and crispness. The hilly areas also have a comparatively low level of insect pests, which makes the produce relatively free of pesticide deposits. As a result, there is a growing vegetable output in the current phase of the state (Sharma & Kumar 2019). The area and production of vegetables in Himachal Pradesh have risen from 2015-16 to 2023-24 (Figure 2). This increase can be explained by the diversification of the area from cereals to high-value vegetables, initiated by higher profitability and shorter crop cycles (Bhatnagar 2025).

Altitudinal variation in the area under vegetable cultivation is pronounced, with the greatest share being accounted by the mid-hill districts like Solan, Sirmaur, Mandi and Kangra due to the nature of road accessibility and closeness to urban markets (Negi *et al.* 2022). The agricultural system in the state is shifting towards high-value cash crop cultivation and a major change in the

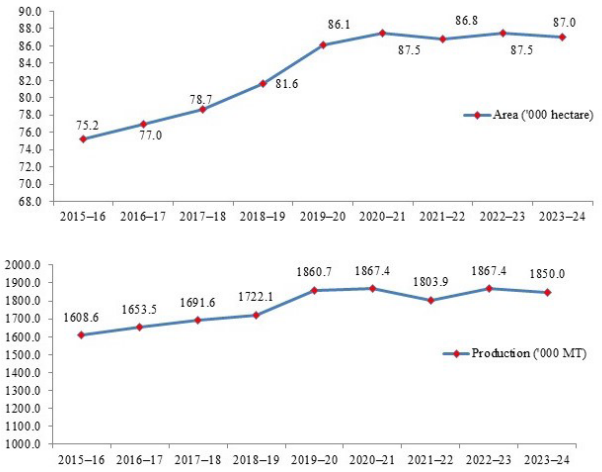


Figure 2. Trends of change in area and production of vegetable crops in Himachal Pradesh (2015-2024). Source: Department of Agriculture, Himachal Pradesh

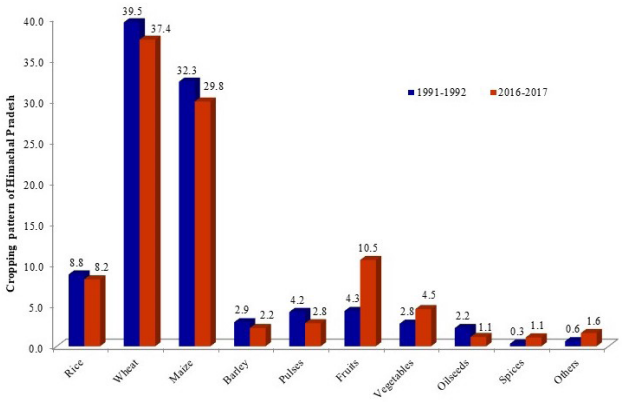


Figure 3. A comparison of the cropping patterns of Himachal Pradesh for major crops. Source: Department of Agriculture, Himachal Pradesh.

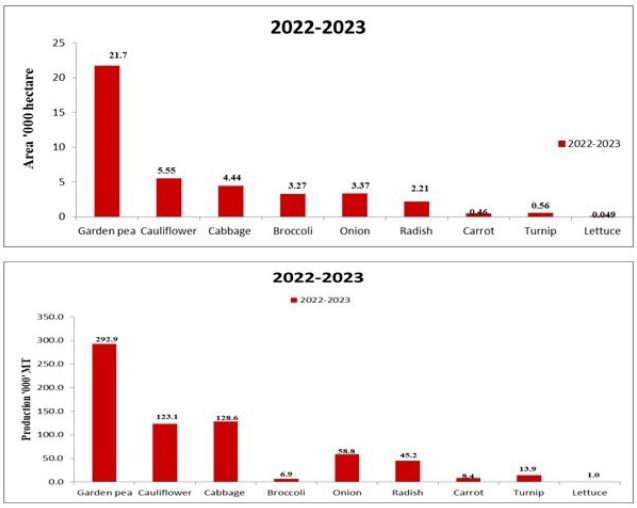


Figure 4. Area and production of temperate vegetable crops in the year 2022-23. Source: Department of Agriculture, Himachal Pradesh.

pattern of cropping in cold climatic areas has been made with the introduction of off-season vegetable crops, making Himachal Pradesh a large producer of off-season vegetables to the rest of the states, especially Punjab, Haryana, Delhi and Uttar Pradesh when temperatures are high in the plains (Singh & Chauhan 2018; Bains & Atlas 2022). In the last 20 years, high-hill districts such as Kullu, Chamba and Kinnaur have also seen significant growth in the area under cole crops, peas and seed potato, supported by government subsidies on off-season farming (Mandla *et al.* 2023). Figure 3 is a comparison of the cropping pattern of Himachal Pradesh of major crops (Chaudhary & Singh 2020).

The area and production under temperate vegetable crops have witnessed a rapid increase in the year 2022-23 (Figure 4). Garden pea has maintained dominance in both area and production of the total temperate vegetables cultivated in the state. Cole crops hold the second position in occupying maximum acreage and production, followed by the root crops like carrot, radish and turnip.

ECONOMIC IMPORTANCE AND CONTRIBUTION TO LIVELIHOODS

In Himachal Pradesh, temperate vegetables have become a significant source of rural income and have contributed greatly to the agricultural gross domestic product (Agri-GDP) of the state. This is an important contribution as agriculture accounts for almost 71 per cent of the state population and is the main source of income for the rural communities (https://naturalfarming.niti.gov.in/himachal-pradesh/). In the aspect of livelihood, vegetable farming yields better returns per unit area than conventional crops. For example, on comparing maize or wheat with cabbage and cauliflower in the same land conditions, net returns were reported to be greater (3-5 times), despite increased costs of input (Singh & Chauhan 2018) for vegetable crops. The job prospects of the sector are also remarkable. Compared to cereals, vegetable farming is

more labour-intensive, creating more jobs in the rural environment, including planting, weeding, harvesting, grading, packaging, and transportation (Paul *et al.* 2016). The highest seasonal labour demand is observed in the harvest period of June to August and October to November when the marginal farmers and the landless labourers obtain wage opportunities (Anonymous 2022-23). In addition, value-chain services, including collection centres, cold storage facilities and transportation services, have generated non-farm jobs, thus increasing economic diversification of the rural areas (Jha *et al.* 2019).

NUTRITIONAL IMPORTANCE

Temperate vegetables are an important part of nutritional security in Himachal Pradesh, especially in the mid- and high-hill regions where cereal-based vegetarian diets predominate. Cabbage, cauliflower, broccoli, carrot, beetroot, radish and garden pea, cultivated in cool climates, are highly rich in vitamin C, β-carotene (provitamin A), vitamin K and folates, along with minerals including iron, calcium, potassium, magnesium and dietary fibre (Yadav & Verma 2024). Consistent intake of these vegetables has been associated with immune resilience, vision, bone health, metabolic regulation and digestive function, whereas dietary fibre is responsible for glycaemic regulation and gut health enhancement (Table 1).

Cole vegetables like cabbage, broccoli and cauliflower contain glucosinolates and their hydrolysed derivatives, including in particular isothiocyanates such as sulforaphane, which are known to be antioxidants, anti-inflammatory and anti-cancerous (Connolly *et al.* 2021). These bioactive compounds position temperate vegetables as functional foods and have the potential for lowering the risk of chronic diseases through sustained consumption. In hill areas, locally grown temperate vegetables are highly accessible and available during colder seasons when other vegetable sources may be limited, thereby supporting year-round dietary diversification and micronutrient sufficiency. Thus, improving both cultivation and consumption of temperate vegetables is not only an agronomic strategy, but also an essential pathway to improve human health, nutrition and sustainable agriculture in Himachal Pradesh.

Table 1. Nutritional composition of major temperate vegetables (per 100 g edible portion)

Vegetable	Energy (kcal)	Protein (g)	Fibre (g)	Vitamin C (mg)	Key bioactives	Health benefits
Cabbage	24–25	1.4	2.4	36–50	Ca, Fe	Immunity, digestion
Cauliflower	25	2.0	2.1	48	Potassium	Antioxidant, immunity
Broccoli	34	2.8	2.6	89	Glucosinolates, Vitamin K	Anti-cancer, anti-inflammatory
Brussels Sprouts	43	3.4	3.8	85–100	Mn, Zn, glucosinolates	Cancer prevention
Kohlrabi	27	2.0	3.6	56	Fibre	Gut health
Kale	35	3.3	1.94	120	Glucosinolates (*e.g.*, sinigrin), phenolic acids, flavonoids, carotenoids (β-carotene)	Anti-inflammatory, Anti-cancer, Antioxidant, Cardiovascular health
Radish	16	0.7	1.6	24	Glucosinolates	Detoxification, digestive aid
Turnip	28	0.9	1.8	21	Iron	Antioxidant, fibre-rich
Carrot	41	1.0	2.8	5.9	**β-carotene (~828 µg)**	Eye health, antioxidant
Beetroot	43	1.6	3.4	4.9	Folate (~109 µg), nitrates	Cardiovascular health
Garden Pea	81	6.5	5.1	40	Plant protein, fibre	Gut health
Spinach	23	2.0	2.5	28	Iron, folate	Anaemia prevention
Lettuce	15–17	1.4	1.3–1.5	9	Chlorophyll, carotenoids (β-carotene, lutein, zeaxanthin)	Improves bone health, antioxidant
Watercress	23	3.0	1.5	43	Calcium, Vit K	Bone health

Source: Sarwat, 2022.

VALUE CHAIN AND MARKETING

The temperate vegetables value chain in Himachal Pradesh consists of a number of stakeholders, including farmers, local suppliers, commission agents, wholesalers, retailers and transportation companies who play a key role in the progression of produce from farm to market (Ankita 2017). A value-chain analysis on peas in Kullu district showed that retailers contributed the maximum (5.9%), followed by wholesalers (3.9%) and local traders (around 2.2%) of total value addition, while farmers reported relatively low contribution owing to infrastructural challenges. Despite the state's leading role in off-season production to the metropolitan markets in Delhi, Chandigarh and Punjab, the structure of the value chain is still largely unorganised, with weak farmer-market linkages and low primary value capture (Bala *et al.* 2011). Institutional mechanisms, including APEDA's Farmer Connect platform, integrated pack houses, cluster-based aggregation and cold-chain development programs supported by Himachal Pradesh State Agricultural Marketing Board (HPSAMB) are suggested to strengthen value-chain governance to further enhance the marketing framework and export-readiness (APEDA 2024; Anonymous 2023c) of the temperate vegetables. Studies of marketing pathways revealed that the four main channels are producer–consumer [A], producer-wholesaler-retailer-consumer [B], producer-local trader/commission agent-wholesaler-retailer-consumer [C] and producer-retailer-consumer [D] (Ankita 2017). The channel with the most intermediaries is Channel C, while using Channel A for direct marketing retains 98% of the consumer rupee. (Ankita 2017). Market intelligence systems with increased sophistication, coordinated collective marketing, grading and minimal processing infrastructure are identified as significant interventions to raise farmer returns against marketing losses.

Levels of market linkages have also intensified remarkably in the past twenty years, where vegetables from Himachal Pradesh reach large wholesale markets in Chandigarh, Delhi, and Punjab every day (Singh *et al.* 2020). The temperate vegetables from Himachal Pradesh are marketed in India, with the greatest share being sold in Delhi (35 per cent), followed by Punjab (20 per cent) and Haryana (15 per cent) and other states in the North (Singh *et al.* 2006). The Himachal Pradesh Horticulture Development Project, the Rashtriya Krishi Vikas Yojana and other government programs have also assisted with infrastructure development, input subsidies and training programs of the farmers (Anonymous 2023a,b). During high seasons of the harvest, farmers have to deal with glut cases, which cause distress sales and income instability (Devi *et al.* 2020). The establishment of Farmer-Producer Organisations (FPOs), cooperative marketing and contract farming has also been proposed as a form of stabilising incomes and enhancing bargaining power (Patil *et al.* 2025).

EXPORT POTENTIAL OF TEMPERATE VEGETABLES

At the national level, temperate vegetables are not categorised separately in export statistics, though temperate and off-season crops like pea, cauliflower, cabbage, broccoli and carrot are included in the "Other Fresh Vegetables" export category. Fresh vegetable exports from the country registered an increase from USD 651.68 million in 2019-20 to USD 926.43 million in 2022-23, showing sustained export demands (Anonymous 2024a). According to APEDA (2024), "Other Fresh Vegetables", which are primarily temperate crops, recorded a major export volume being exported to the United Arab Emirates, Bangladesh, Nepal, the United Kingdom, Oman, Sri Lanka and Qatar. During the Triennium Ending (TE) 2020-21, temperate vegetables made up 25.14% of quantity and 20.91% of export value, highlighting their importance in the external trade (Pal *et al.* 2023). Despite limited direct export of vegetables from Himachal Pradesh, it plays a major contributing role towards the supply chain by channelling the produce to large aggregation and export centres like Delhi (Azadpur), Chandigarh and Punjab. In order to strengthen exports of temperate vegetables from Himachal Pradesh, measures such as cluster-based production, GLOBALG.A.P. certification and improved post-harvest facilities like pack houses, grading and pre-cooling units (APEDA 2024) are urgently required as temperate vegetables possess strong export potential.

CLIMATE CHANGE IMPACTS AND RESILIENCE STRATEGIES

Climate change has increasingly affected the temperate vegetable production in Himachal Pradesh, as has been evident through systematic observation and study of meteorological records over the last 30 years. Wide research work by agricultural as well as meteorological departments has recorded immense changes in temperature patterns, precipitation patterns and severe weather events that directly affect the crop-production systems (Singh *et al.* 2025a; Joshi & Verma 2020). During winter months, the warming tendency is more pronounced than in the summer months (Rahim *et al.* 2023), significantly affecting chilling hour accumulation required for vernalisation of temperate vegetables. Increases in minimum temperature (1.2-1.6°C) have outpaced the maximum temperature (0.4-0.8°C), leading to a decrease in diurnal temperature that can further change plant physiological functions (Wagholikar *et al.* 2014). The strongest temperature rise in high altitude areas has pushed the thermal zones upwards by 150-200 m in altitude, thus altering the traditional cultivation areas and forcing cropping patterns of farmers to change (Shrestha *et al.* 2012; Sati 2024).

Increased heat stress during the critical growth periods (especially flowering and fruit development) has become more frequent with temperatures exceeding 30°C, sustained over long durations in the mid-hill regions (Singh *et al.* 2025b). Growing-degree-day (GDD) accumulations have increased in various zones, which have increased crop development speed and reduced effective growth of temperature-sensitive crops (Krishnan *et al.* 2019). This acceleration in growth influences the quality of crops and is especially relevant to potatoes, where quick bulking lowers dry content and quality of storage (Han *et al.* 2025). The increase in frost-free periods has been extended by 15-25 days, which has not only enabled the longer growing seasons but has also resulted in an increase in the pests and disease pressure (Krishnan *et al.* 2019; Das *et al.* 2023). The spatial and temporal variability of the precipitation patterns is pronounced, with overall declining trends in annual rainfall in the majority of the districts (Anonymous 2023d). A rise in the intensity and frequency of extreme precipitation events has occurred, with heavy rainfall days (>50 mm) increased by 15-20 per cent while decreasing total rainy days. This pattern increases runoff, soil erosion and floods during intense events followed by extended dry periods that stress crops.

Agricultural institutions and farmers in Himachal Pradesh have devised and adopted various adaptation policies to reduce the effects of climate change without compromising the productivity and profitability (Thakur *et al.* 2023). These measures include technological, agronomic and institutional measures that enhance the agro-ecosystems of temperate vegetables production. The utilisation of climate-resistant varieties and tolerant genetic sources to combat climatic stresses in temperate vegetable crops is one of the main adaptation methods and has been summarised in Table 2. Superior heat-tolerant potato cultivars like Kufri Surya and Kufri Pukhraj are encouraged to be planted in warmer zones of mid-hills (Singh & Lal 2015). Drought-tolerant peas and beans permit farming under water-restricted conditions. Staggered planting schedules help distribute climate risks and ensure a continuous market supply. Participatory plant-breeding projects involve farmers in the development of locally adapted varieties suited for altered climatic conditions. Protected cultivation offers controlled environments to the crops against harsh weather events and enables their year-round production (Bala & Rana 2022). Low-cost protective structures such as shade nets and low tunnels provide affordable protection for the small farmers (Rana *et al.* 2018). Climate-smart Integrated Pest Management (IPM) measures adapt to evolving pest and disease stresses under altered climatic conditions (Bouri *et al.* 2023). Weather-based disease-forecasting models assist farmers in scheduling preventive applications effectively (Vennila *et al.* 2016). Planting of resistant varieties offers durable protection against key diseases and reduces the dependence on pesticides (Iqbal *et al.* 2025). The training programs also help in improving the knowledge and skills of farmers on how to adopt IPM strategies effectively (Sekabira *et al.* 2022).

CRITICAL CHALLENGES AND CONSTRAINTS

Regardless of the substantial degree of progress, temperate vegetable cultivation in Himachal Pradesh

Table 2. Climatic stress–resistant sources for temperate vegetable crops

Crop/group	Climatic stress	Resistant/tolerant source(s)	Type of material	Key notes (relevance for temperate / hill regions)
Carrot (*Daucus carota*)	Salinity	'Kuruda' (vs 'Shundori')	Cultivars	Pot experiment showed Kuruda relatively more salt-tolerant than Shundori up to 150 mM NaCl (smaller reductions in growth and root yield). Suitable as a donor for salinity tolerance.
Carrot	Heat / high temperature	'Pusa Vrishti' (tropical red carrot)	Open-pollinated variety	Bred as a heat-tolerant tropical carrot, performs well at higher temperatures where European temperate types fail, relevant for warm lower hills and extended season cropping.
Cole crops (*Brassica oleracea* cabbage, cauliflower, broccoli, *etc.*)	Heat / terminal heat	B. oleracea wild forms, related species)	Cultivars + wild relatives	Heat-tolerant cabbage lines and use of wild species for heat tolerance in broccoli and cabbage; important for late planting and warm autumns in hills.
Cabbage	Heat / high temperature	Landrace accessions from India and Pakistan	Cultivars + wild relatives	-
Broccoli	Heat / high temperature	Wild Brassica species, *e.g.*, *B. oleracea* var. *sylvestris, B. villosa*	Cultivars + wild relatives	-
Kale	Heat / high temperature	Cultivars 'Red Russian', 'Lacinato'	Cultivars + wild relatives	-
Cauliflower (*Brassica oleracea* var. *botrytis*)	High temperature/ curd *initiation* under warm conditions	Indian heat-tolerant "early" and "medium" cauliflower groups; varieties like Pusa Snowball K-1, Pusa Sharad	Cultivars/ maturity groups	These groups maintain curd formation at relatively higher temperatures, enabling off-season production in mid-hills and warm pockets.
Broccoli (*Brassica oleracea* var. *italica*)	Cold/freezing stress (seedling stage)	'Meiqing' (strongest); followed by 'King 11', 'Zhongqing 15', 'Meiao 7172', 'Zhongqing 318', 'Zheqing 80', 'Zhongqing 16', 'Zhongqing 319', 'Lvxiong 90'	Cultivars	At 2/–5 °C cycles, 'Meiqing' showed the highest cold tolerance, with several others moderately tolerant; useful models or donors for cold-hardy broccoli suited to high elevations.
Broccoli	Heat / high temperature (seedling stage)	14 Chinese broccoli cultivars (heat-tolerant types identified; names in article tables)	Cultivars	A multi-trait phenotyping system identified cultivars with higher thermotolerance (lower damage, better physiological status) at elevated temperatures; lines can be used as donors in breeding for warmer climates.
Broccoli (sprouting broccoli)	High temperature effects (mechanistic)	Identification of metabolic traits associated with HT tolerance (proline, phenolics, *etc.*)	Physiological traits/ selection criteria	Study across developmental stages shows which metabolic traits are most responsive to HT and can be used as indirect selection indices for heat-resilient broccoli.
Garden Pea (*Pisum sativum*)	Heat / high temperature (flowering & pod set)	26 highly heat-tolerant accessions (IDs listed in Wang et al. 2022) from screening of 422 pea germplasm	Germplasm accessions	Large-scale screening identified accessions with high heat-tolerance scores and better yield under heat, valuable donors for breeding climate-resilient garden/field peas.

Table 2. *Continued*

Crop/group	Climatic stress	Resistant/tolerant source(s)	Type of material	Key notes (relevance for temperate / hill regions)
Garden Pea	Heat / terminal heat & drought interaction	Multiple tolerant lines summarised in recent pea-heat-stress reviews (IDs and sources tabulated in those papers)	Germplasm sets	Candidate heat-tolerant pea lines and traits such as canopy temperature, pollen viability and pod retention under stress; useful for trait-based selection.
Garden Pea	Cold / winter hardiness	214 highly cold-resistant accessions were identified among 3672 pea accessions	Germplasm accessions	Screening for winter hardiness identified large numbers of frost-tolerant peas, useful for overwintering and high-altitude temperate systems.
Garden Pea (*Pisum sativum*)	Frost stress	ATC 104, ATC 377, ATC 968, ATC 3992, ATC 4204	Germplasm accessions	Confirmed frost tolerance under controlled tests
Garden Pea (winter pea)	Frost / sub-zero tolerance	Winter-hardy peas from a panel of 672 accessions used in GWAS for frost tolerance	Germplasm panel	Marker–trait association study identified winter-hardy genotypes and QTLs for frost tolerance, relevant to snow-prone temperate hills.

still faces a complex set of challenges which jeopardise the sustainability and limit growth potential in the long term. These challenges require systematic attention and coordinated interventions to ensure continued sector development. Climate change is the most immediate threat in the north-western Himalaya with documented temperature increase by 0.8-1.2°C over the past three decades, affecting crop phenology and yield patterns (Tewari *et al.* 2017). Water shortage affects vegetable-growing areas during critical growth periods as declining groundwater levels and reduction in snowfall intensify irrigation deficits in high-altitude areas (Bhusal *et al.* 2018). Weak indigenous seed production is also a major constraint in temperate vegetable cultivation, as it restricts the availability of locally adapted, climate-resilient and disease-tolerant varieties suited to hill agro-ecosystems. Input constraints such as lack of quality seeds, high production costs (fertiliser) and lack of adequate plant protection measures lower the efficiency of field operations. The pressure of pests and diseases is augmented by climate change and intensive cultivation, demanding enhanced region-specific Integrated Pest Management (IPM) strategies and resistant varieties (Bala *et al.* 2021). Lack of proper post-harvest infrastructures like cold storage, packing houses and processing units results in 25–35% post-harvest losses (Bhardwaj *et al.* 2011) and limits value addition opportunities. High transportation costs and lack of connectivity to the remote villages limit the market access and price realisation (Ankita 2017). The price volatility with seasonal variations generates income uncertainty and crop planning difficulties for farmers (Thakur *et al.* 2024). Limited processing capacity utilisation and weak farmer-processor relationships deter value addition and income enhancement. Moreover, inconsistency in quality coupled with a lack of standardisation inhibits competitiveness in premium domestic and export markets (Devkota & Sharma 2014). Addressing these multifaceted challenges requires an integrated strategy incorporating climate-resilient varietal development, efficient resource management, value-chain strengthening and institutional innovation to secure the long-term sustainability of the temperate vegetable sector in Himachal Pradesh.

PROSPECTS AND STRATEGIC RECOMMENDATIONS

The trajectory of temperate vegetables cultivation in Himachal Pradesh is progressively shaped by shifting consumer preferences, technological progress and supportive policy frameworks (Devi & Prasher 2018). Due to the growing health awareness of the population, there is a growing demand for produce that is safe, traceable and rich in nutrients, which opens

opportunities for vegetables to acquire a premium position in Himachal Pradesh (Verma *et al.* 2020). The growing urban development is also fuelling the need to have ready-made and frozen vegetable products (Paul *et al.* 2016). Himachal Pradesh can leverage its "mountain-grown" image to supply these premium segments with the help of efficient branding, certification programs and enhanced logistics. Sustainable growth pathway depends on an integrated strategy involving productivity, future technology and market performance (Chandel *et al.* 2025). Indigenous seed production of temperate vegetables also has promising prospects by strengthening the self-reliance and sustainability of hill agro-ecosystems. Systematic conservation of indigenous adapted landraces, their seed multiplication and integration with participatory breeding programmes would decrease dependence on the costly imports of hybrid varieties, preserve genetic diversity and improve long-term productivity. Strengthening market infrastructure, including cluster-based cold chains, pack houses and processing units, through public-private partnerships can reduce losses and create rural employment (Thakur *et al.* 2024). Empowering Farmer Producer Organisations (FPOs), endorsing digital traceability and assisting innovation ecosystems, including agri-tech startups, training centres and incubating centres, will be more competitive (Ankita 2017). All these interventions will enable Himachal Pradesh to be a model of climate-smart, value-based and competitive horticulture in the Himalayan region.

CONCLUSIONS

In Himachal Pradesh, temperate vegetable cultivation has evolved from subsistence-level farming to a commercially driven, technologically advanced and economically ground-breaking sector. It plays an important role in local livelihoods, contributing significantly to agricultural GDP and providing a year-round off-season supply of vegetables to major markets of North India. However, the sustainability of the sector is vulnerable to climate change impacts, substandard infrastructure, poor market merger, high input costs and limited technological competence at the farm level. Bridging the prevailing yield and resource-efficiency gaps necessitates enforcement of advanced agronomic practices, precision agriculture, climate-resilient varieties and substantial use of protected cultivation. Strengthening indigenous seed production of temperate vegetables is essential for reducing dependence on imports, thus preserving genetic diversity, enhancing local self-reliance and fostering sustainable, climate-resilient horticulture. Upgrading post-harvest facilities, refining logistics, strengthening Farmer-Producer Organisations (FPOs) and establishing market intelligence systems will decrease further losses and improve cost-effectiveness. Amalgamation of modern agricultural technologies, digitalisation and high-value vegetable diversification, including hydroponics, vertical farming and functional foods, can further enhance the competitiveness and export potential of temperate vegetables in the world market. Policy support must focus on risk mitigation techniques, capacity building and multi-stakeholder collaboration. By chasing a climate-smart, innovation-centric, value-chain-strengthened approach, Himachal Pradesh can evolve into a national model for sustainable temperate vegetable horticulture in mountainous ecosystems.

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