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Land Use Dynamics and Challenges in Leh District: A Temporal Analysis of Recent Three Decades

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Abstract: The cold arid region of Ladakh, India, presents unique challenges to agriculture due to its harsh climate, limited arable land, and increasing pressures from population growth, tourism, and climate change. This study examines land use dynamics, agricultural productivity, and food security in Leh District, analyzing how these factors interact with socioeconomic and environmental changes. Using data from the Ladakh Autonomous Hill Development Council and other regional sources spanning 1985-2019, land use patterns, agricultural practices, and livestock contributions have been assessed and analyzed. Findings indicate that while the area under cultivation remains static, intensification and diversification of farming practices are critical for meeting food demands and enhancing livelihoods. While challenges like soil erosion, water scarcity, and land degradation threaten agricultural productivity, opportunities such as protected cultivation, high-value crops, and renewable energy provide viable pathways to sustainability. Policy recommendations highlight the need for technological innovation, sustainable land management, and value-added processing to strengthen food security and enhance economic resilience in this fragile ecosystem.

Key words: Ladakh, land use, food security, agriculture, cold arid, sustainability.

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The cold, arid region of Ladakh, located within the trans-Himalayan landscape of India, exemplifies one of the most ecologically fragile and climatically extreme inhabited environments in the world. Situated at high altitudes and marked by minimal precipitation, low humidity, and wide temperature fluctuations, Ladakh is characterized by sparse vegetation and limited arable land. Despite these severe biophysical constraints, agriculture has long served as the foundation of Ladakh's subsistence economy, sustaining small, dispersed settlements through intricate agro-pastoral systems that integrate crop cultivation and livestock rearing (Tiwari, 2000). In recent decades, rapid socioeconomic transformations—particularly the expansion of the tourism sector, which now contributes nearly 50% of Ladakh's GDP—combined with urban growth and increasing climate variability, have fundamentally altered land use patterns and intensified threats to regional food security (Dame and Nüsser, 2011).

Land use change functions as a pivotal driver of environmental and social transformation, influencing biodiversity, greenhouse gas emissions, and hydrological systems (Chan *et al*., 2017). In Ladakh, the relationship between land use, agricultural productivity, and food security is complex and multidimensional, shaped by local demographic changes, shifting dietary preferences, and broader economic realignments associated with tourism (Gaur and Squires, 2018). Environmental pressures such as soil erosion, glacier retreat, and water scarcity has exacerbated this situation, threatening the continuity of traditional agricultural systems reliant on glacial meltwater for irrigation. Declining snowfall and accelerated glacier recession have reduced water availability, under mining the reliability of irrigation sources and increasing vulnerability to climatic shocks (Gaur *et al*., 2021). Furthermore, frost shattering, high winds, and ongoing desertification processes continue to degrade cultivable soils, limiting agricultural potential and productivity (Gaur *et al*., 2019).

Leh District, the largest in India, encompasses an area of 45,110 km² and lies between 32°–36° N latitude and 75°–80° E longitude at an average elevation exceeding 3,000 m. As of the 2011 Census, its population stood at 133,487, distributed across 112 villages, yielding an average population density of merely three persons per square kilometre (LAHDC, 2011). The geomorphology of Leh reflects a landscape sculpted by tectonic uplift and glacial processes, characterized by rugged mountain ranges, deep valleys, and morainic deposits. The Indus River and its tributaries—such as the Zanskar and Shyok—carve out narrow alluvial plains that provide the region's limited agricultural zones. Soils in these areas are skeletal, rocky, calcareous, and low in organic matter due to the combined effects of aridity, low temperatures, and weak pedogenic activity (Gupta and Arora, 2017). The climate is severe, with temperatures ranging from –40°C in winter to 30°C in summer, and annual rainfall averaging less than 100 mm, primarily in the form of snow (Fig. 1). Intense solar radiation (6–7 kW m□²), coupled with strong winds and low humidity, further intensifies aridity, while a short growing season from May to September restricts agricultural activity to areas irrigated by glacial meltwater (Santra, 2016).

Within this narrow ecological margin, agriculture is concentrated along the Indus, Zanskar, and Shyok river basins. Approximately 10,319 ha of land are cultivated, dominated by barley (3,631.4 ha) and wheat (2,414.5 ha) (LAHDC, 2012). These grains form the dietary and cultural core of Ladakh's traditional food systems, with barley-based products such as *tsampa* (roasted barley flour) and *chang* (barley beer) holding both nutritional and cultural importance (Dame and Nüsser, 2011). The increasing demand from the tourism industry and the Indian military has stimulated growth in vegetable cultivation, which now covers about 5.5% of agricultural land. Potatoes (75.6%), peas (10.7%), and onions (3.4%) are the major vegetable crops, with Leh block accounting for 52.6% of the total vegetable area and producing 55.4% of the district's annual output of 11,867 tonnes (LAHDC, 2012). This expansion has improved household incomes and diversified local diets, enhancing both economic and nutritional resilience (Ehlers and Kreutzmann, 2000).

Horticulture, particularly the cultivation of apricots, apples, and sea buckthorn, has emerged as a significant component of livelihood diversification. Khaltsi block leads in apricot production, where fruit dehydration techniques are employed to reduce post-harvest losses and extend marketability (Sharma and Mir, 2000). Sea buckthorn, valued for its rich vitamin content and medicinal properties, has gained prominence as a high-value crop with diverse industrial applications. Its processed derivatives—juices, oils, and nutraceuticals—offer considerable economic potential for smallholder farmers (Saxena *et al*., 2018). Though average landholdings have declined from 1.38 ha in 1995–96 to 0.68 ha in 2015–16 (LAHDC, 2012), but diversification has become vital to maintaining livelihood security.

Livestock rearing continues to underpin the agrarian economy, engaging over 70% of the working population as cultivators, herders, and agricultural laborers (Darku *et al*., 2016). Between 2003 and 2012, the total livestock population increased marginally from 399,100 to 414,808, though its composition changed significantly. Goats have remained dominant, comprising over 50% of the total livestock population, while sheep numbers declined from 25.6% to 19.6%. In contrast, cattle and Dzo–Dzomo

populations have increased, reflecting a growing emphasis on dairy production, and poultry has emerged as a new sector contributing over 8% of total livestock by 2012. The populations of yaks and demos have decreased from 7.4% to 3.9%, illustrating shifting economic and ecological priorities. The Changthangi goat, primarily raised in Nyoma and Durbuk blocks, produces the globally prized pashmina wool, which sustains rural economies through high-value textile production. Yaks continue to provide milk, meat, fiber, and draught power in high-altitude areas, while improved cattle breeds in Leh block enhance milk yields to meet household and market needs (Akand *et al.*, 2017). Manure from livestock serves as an essential organic input, replenishing soil nutrients and maintaining the cyclical flow of resources within the traditional agro-pastoral system (Kreutzmann, 2006).

Despite these adaptive strategies, Ladakh faces mounting challenges to food security. Rapid urban expansion and tourism-driven development have encroached upon arable land, while climate-induced water shortages further constrain production. Consequently, more than 60% of Ladakh's food supply now depends on imports from outside the region (Dame and Nüsser, 2011). These dynamics highlight the urgency of enhancing agricultural resilience and sustainability. Recent technological interventions, including protected cultivation systems, solar-powered irrigation, and geospatial mapping tools, offer promising opportunities for improving productivity and resource management (Gaur *et al.*, 2024). The application of remote sensing and GIS has proven effective in analyzing land use patterns, soil characteristics, and environmental constraints, generating data-driven insights that can inform sustainable policy decisions.

Ensuring long-term resilience in Ladakh's agricultural systems requires a balanced integration of modernization and ecological stewardship. Diversification into high-value crops, adoption of climate-resilient technologies, and promotion of sustainable agro-tourism can strengthen livelihoods while preserving the fragile ecosystem. However, technological innovation alone is insufficient. Sustained food and livelihood security will depend on protecting Ladakh's traditional agro-pastoral knowledge and adaptive cultural practices, which embody centuries of ecological wisdom. The future of agriculture in this high-altitude desert thus lies in maintaining a careful equilibrium between development and conservation, ensuring that progress does not come at the cost of ecological and cultural integrity.

Materials and Methods

The present study draws on secondary data from the Ladakh Autonomous Hill Development Council (LAHDC) Statistical Handbooks,

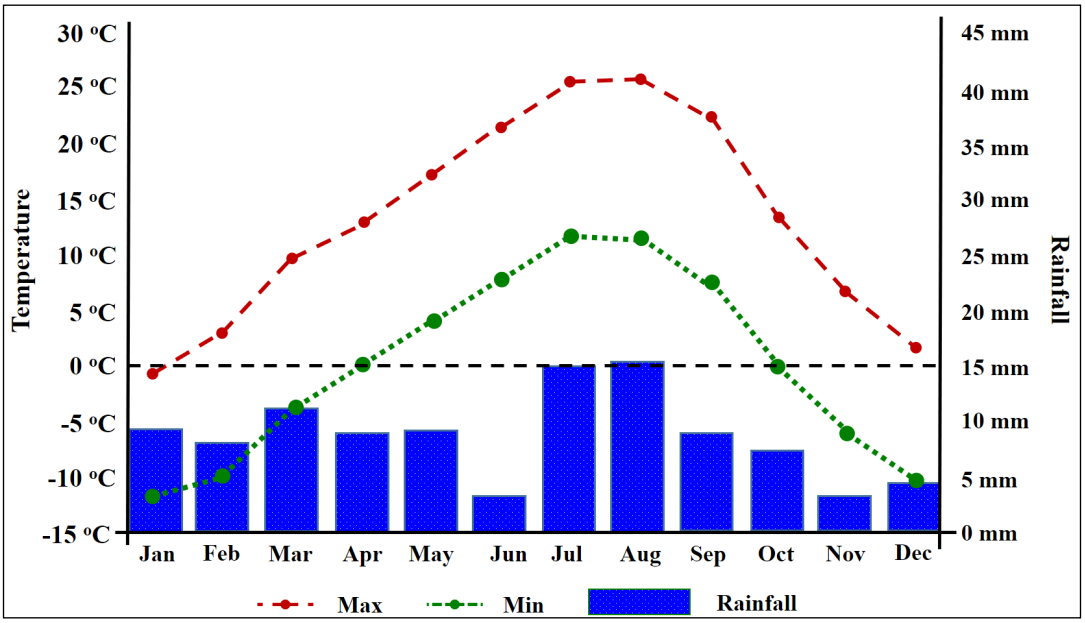

Fig. 1. Climate chart of Leh district (India).

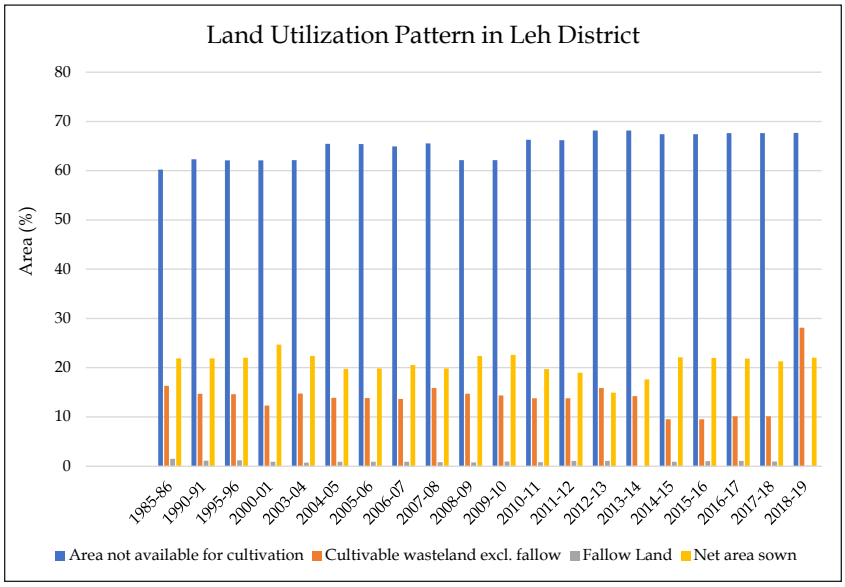

Fig. 2. Land utilization pattern in Leh district (1985-86 to 2018-19).

the Financial Commissioner (Revenue) of Jammu and Kashmir, and the Agriculture and Livestock Censuses (1985-2019). Data on land use patterns, including net area sown, fallow land, cultivable wasteland, and areas not available for cultivation, were analyzed to assess temporal changes. Agricultural productivity data, including crop yields and livestock contributions, were sourced from the Deputy Commissioner's Office, Leh, and the Animal Husbandry Department. Horticultural data were obtained from regional reports on fruit and vegetable production.

Qualitative statistics were drawn from field observations and existing literature on Ladakh's agro-pastoral systems (Osmaston, 1994; Sharma and Mir, 2000). Descriptive statistics were used to quantify land use changes, expressed as percentages of the total reporting area. Relative changes in land use categories were calculated to highlight trends over time. The study also incorporates spatial data on soil erosion and land degradation from geospatial analyses (Gaur *et al.*, 2019).

Results and Discussion

Land use dynamics

Land use in Leh District, a high-altitude cold desert located in the trans-Himalayan region of India, is profoundly influenced by its arid environment, rugged topography, and extreme climatic conditions. With 67.7% of the total reporting area classified as not available for cultivation in 2018-19, primarily due to barren mountains, rocky outcrops, and desert landscapes, the region's agricultural potential is severely constrained (LAHDC, 2012). The net area sown, which represents the actively cultivated land, peaked at 24.7% of the total reporting area in 2000-01 but declined significantly to 14.9% by 2012-13, reflecting a shift toward non-agricultural uses (Gaur *et al.*, 2024). By 2016-18, urban development and tourism-related infrastructure had increased to 16.2% of the land area, up from just 4.1% in 1985–86, driven by the region's booming tourism industry, which contributes 50% to Ladakh's GDP (Dame and Nüsser, 2011). Cultivable wasteland, including areas under miscellaneous trees, grooves, and degraded pastures, fluctuated over the study period, reaching a high of 28.1% in 2018–19 (Fig. 2). Fallow land, however, remained minimal, dropping to 0.11% in 2018–19, indicating intensive use of the limited arable land available (Gaur, 2025).

Temporal trends in land use

The temporal analysis of land use data from 1985 to 2019 revealed significant shifts driven by both environmental and anthropogenic factors. Data from the Ladakh Autonomous Hill Development Council (LAHDC) Statistical Handbooks and the Financial Commissioner (Revenue) of Jammu and Kashmir show that the net area sown declined by approximately 10% over the three decades, with a notable

acceleration in land conversion after 2000. This period coincided with rapid urban expansion in Leh city and surrounding areas, where 8% of agricultural land was lost to construction between 1969 and 2019 (Gaur *et al*., 2024). For instance, between 2003 and 2019, approximately 9,400 new buildings were constructed, primarily for tourism-related infrastructure such as hotels, guesthouses, and roads, reflecting a 3.5% annual increase in built-up areas. This urban sprawl has encroached on fertile alluvial plains along the Indus, Zanskar, and Shyok Rivers, which are critical for agriculture due to their access to glacial meltwater irrigation (Gaur *et al*., 2024).

Figure 2 also illustrates the distribution of land use across four categories—area not available for cultivation, cultivable wasteland excluding fallow, fallow land, and net area sown—over a period spanning from 1985-86 to 2018-19. This visual representation provides insights into the land utilization in the Leh District, reflecting changes influenced by agricultural practices, environmental conditions, and land management policies.

The dominant category throughout the period is the "Area not Available for Cultivation," consistently occupying the highest percentage, typically ranging between 60% and 70%. This indicates that a significant portion of the land in Leh District is unsuitable for farming, due to factors such as rugged terrain, high altitude, restricted period for agricultural activities and cold arid conditions. The stability of this category suggests limited changes in the overall land availability for agriculture over the decades, with minor fluctuations observed, such as a slight increase around 2012-13 and 2017-18.

The "Net Area Sown" category, which represents the land actively used for cultivation, shows a relatively stable trend, generally fluctuating between 10% and 20%. A noticeable increase occurs around 1985-86 and 2018-19, where the percentage reaches 20%, indicating periods of increased agricultural activity. However, there are exceptions, such as in 2011-12 and 2013-14, when the value fall below 10%, possibly reflecting challenges like water scarcity and reduced farming interest among the younger generation. The "Cultivable Wasteland excluding Fallow" and "Fallow Land" categories remain minor contributors, typically ranging from 5% to 15% and 0% to 10%, respectively, with occasional spikes (e.g., Cultivable Wasteland peaking around 2017-18 at nearly 20%). This suggests that while some land is potentially cultivable, it remains underutilized, and fallow periods are minimal, likely due to the harsh climate limiting extensive land rotation.

Overall, the land utilization pattern in Leh District reveals a consistent reliance on a small proportion of land for active cultivation, with the majority remaining unavailable due to natural constraints. The gradual increase in

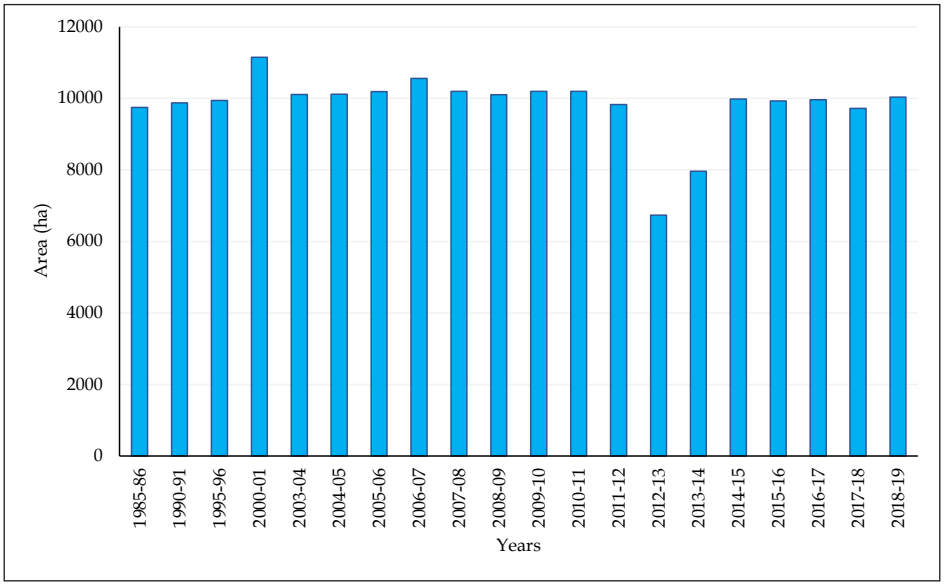

Fig. 3. Net Sown Area (ha) in Leh District (1985-86 to 2018-19).

net sown area towards 2018-19, alongside a rise in cultivable wasteland, reflects on efforts to expand agricultural land or improve land management practices. However, the persistent high percentage of land not available for cultivation underscores the ongoing challenges faced by agriculture in this region over the 34-year period.

The Figure 3 presents a comprehensive overview of the agricultural land usage in the Leh District over a span of about three decades. From 1985-86 to 2000-01, the net sown area in Leh District exhibited a relatively stable trend, with values fluctuating between approximately 9,000 and 11,000 ha. A notable hike was observed around 1995-96, when the area reached 11,144 ha, suggesting a period of increased agricultural activity or favorable conditions. However, this was followed by a slight decline and stabilization in the subsequent years, indicating possible challenges or shifts in land use during the late 1990s and early 2000s.

Between 2003-04 and 2010-11, the net sown area remained around 10,000 ha, with minor variations. This period of stability suggested a sustained agricultural base, potentially supported by consistent farming practices as well as irrigation infrastructure. However, a significant decline was observed around 2011–12 and 2012–13, when the area fell to approximately 6,000 ha- the lowest level of land utilization recorded during the period. This decline could be attributed to factors such as environmental changes, water scarcity, and shifts in economic priorities. From 2013–14 onwards, a gradual recovery and stabilization are observed, with the net sown area increasing to approximately 9,000–10,000 ha by 2018–19. This upward trend in the later years suggests the adoption of adaptive measures and improvements in agricultural infrastructure. However, the occasional dips reflect both the resilience of the ongoing challenges faced by agriculture in the Leh District over the 34-year period. There has been an increase in cultivable wasteland, peaking at 28.1% in 2018-19. It is partly attributed to the abandonment of marginal agricultural lands. Factors such as water scarcity, driven by glacier retreat and erratic snowfall, have rendered some fields unsustainable for cultivation (Gaur *et al.,* 2021). Additionally, socioeconomic changes, including migration to urban areas and alternative income opportunities in tourism, have led to a rise in fallow or underutilized lands, particularly in remote blocks like Nyoma and Durbuk. Despite this, the minimal fallow land (0.11% in 2018-19) underscores the intensive farming practices in areas where irrigation is available, as farmers maximize the short growing season (May–September) to meet food and livelihood needs (Gaur *et al.,* 2024).

Spatial patterns and environmental constraints

Spatially, land use in Leh District is highly heterogeneous, with agricultural activity mainly concentrated in narrow alluvial valleys along river systems. The Indus River and its tributaries, such as Zanskar and Shyok, support 10,319 ha of agricultural land, with Leh block accounting for 52.6% of cultivated areas due to its relatively flat terrain and access to irrigation (LAHDC, 2012). In contrast, high-altitude blocks like Nyoma and Durbuk have limited arable land, with only 10 to 15% of their area suitable for cultivation due to steep slopes and poor soil development (Gupta and Arora, 2017). Geospatial analyses indicate that soil erosion and land degradation are significant challenges, particularly in the Shyok sub-basin, where frost shattering (36.21%) and wind erosion (7.37%) have degraded 24% of the land area (Gaur *et al*., 2019). These processes are exacerbated by the region's skeletal, calcareous, and alkaline soils, which have low organic matter and are prone to erosion under the influence of snowmelt and high winds (Gupta and Arora, 2017; Gaur *et al*., 2024).

The spatial distribution of land use changes also reflects the impact of tourism-driven development. In Leh block, the conversion of agricultural land to urban uses is most pronounced, with satellite imagery showing a 12% reduction in cultivated fields near Leh city between 2000 and 2015 (Gaur *et al*., 2021). In contrast, remote blocks like Khaltsi have seen slower rates of land conversion but face increasing pressure from tourism-related water extraction, which competes with agricultural irrigation needs. The groundwater overuse by hotels and tourist facilities, requiring thousands of water tankers daily, has led to the drying up of springs and irrigation channels, forcing some farmers to abandon fields (Gaur and Goyal, 2022).

Drivers of land use change

There are numerous and interconnected drivers of land use change in Leh District. The tourism boom, particularly since the early 2000s, has driven significant land conversion, as the construction of tourism infrastructure has not only reduced arable land but also increased land prices, making it economically viable for farmers to sell or lease agricultural plots for non-agricultural purposes (Dame and Nüsser, 2011). This trend is especially prominent in Leh city and along major highways, where agricultural fields have been replaced by commercial establishments. Climate variability also plays a critical role; declining snowfall and glacier retreat—evidenced by over 80% of glaciers smaller than one square kilometer exhibiting negative mass balance—have diminished meltwater availability for irrigation (Gaur *et al*., 2021), leading to the abandonment of fields in water-scarce areas and an increase in cultivable wasteland (Gaur *et al*., 2024). Socioeconomic shifts further influence land use; the average landholding size has decreased from 1.38 hectares in 1995–96 to 0.68 ha in 2015–16, reflecting land fragmentation driven by population growth and inheritance patterns (LAHDC, 2012). Additionally, a shift toward non-agricultural livelihoods, especially tourism and government employment, has reduced labor availability for farming, resulting in underutilized or fallow lands (Hinz *et al*., 2020). Environmental degradation also contributes to land use change; processes such as frost shattering, wind erosion, and vegetation degradation have rendered significant portions of land unsuitable for cultivation. For example, in the Shyok sub-basin, 3.04% of land is affected by vegetation degradation, further limiting agricultural expansion (Gaur *et al*., 2024).

Implications of land use change on agriculture and sustainability

The decline in net area sown and the increase in non-agricultural land use pose significant challenges to agricultural productivity and food security in Leh District. The loss of fertile alluvial lands to urbanization reduces the region's capacity to produce staple crops like wheat and barley, increasing reliance on food imports, which account for over 60% of food needs (Dame and Nüsser, 2011). This dependence is particularly risky during winter months when road access is limited, highlighting the need for strategies to enhance local production. The intensive use of available arable land, as evidenced by minimal fallow areas, places additional pressure on soil and water resources, exacerbating degradation and reducing long-term sustainability (Gaur and Squires, 2020).

However, these challenges also present opportunities for sustainable land management. The increase in cultivable wasteland suggests potential for reclamation through soil conservation techniques, such as terracing, contour farming, and organic amendments, which could restore degraded lands for agriculture (Gaur, 2025). Additionally, the adoption of protected cultivation technologies, such as greenhouses and trench farming, can mitigate the impact of land loss by enabling year-round production on smaller plots (Santra, 2016). The integration of high-value crops, such as sea buckthorn and medicinal plants, into degraded or marginal lands could further enhance land use efficiency and economic resilience (Saxena *et al*., 2018).

Food security dynamics and socioeconomic changes

Agriculture and livestock are critical to food security, providing locally produced grains, vegetables, and animal products that sustain communities during the harsh winter months when Ladakh is cut off from external supplies. However, the region meets over 60% of its food requirements through imports, facilitated by the Public Distribution System (PDS), which supplies subsidized wheat, rice, and sugar. This reliance has reduced local wheat cultivation, as households opt for PDS supplies, but it has also increased vulnerability to supply chain disruptions. Livestock products, particularly milk and meat, fill critical nutritional gaps, with milk contributing up to 80% of dietary fat in Nyoma block. The cultural preference for barley-based foods ensures their continued production despite import availability, maintaining a degree of food sovereignty (Gaur *et al*., 2024).

The integration of crop and livestock systems enhances resilience by diversifying food sources and income streams. The mixed crop-livestock farming in Leh valley combines cereal fields, fruit trees, community pastures, and livestock,

creating a socio-economically sustainable model. However, declining agricultural land and increasing fallow fields, driven by income diversification and urban migration, threaten this system's long-term viability (Hinz *et al*., 2020). Smallholder farms, constituting 93% of operational holdings, face economic challenges due to land fragmentation, with 3–5% of land lost to boundaries and hedges (Gaur, 2025). Despite these constraints, agriculture and livestock remain vital for sustaining livelihoods and ensuring food security in a region where alternative employment opportunities are limited (Squires and Gaur, 2020).

Despite these challenges, opportunities exist for agricultural intensification. Protected cultivation, such as greenhouses and trench farming, has extended the vegetable season, enabling year-round production of crops. High-value crops, including medicinal plants (like *Rhodiola imbricata*) and mushrooms, offer income diversification, while solar energy technologies, leveraging Ladakh's high insolation (7–7.5 $kWh^{-1}\ m^{-2}\ day^{-1}$), support irrigation and greenhouse heating (Santra, 2016). These innovations could reduce import reliance and enhance local food production.

Future challenges and opportunities for sustainable agricultural development

The agricultural sector in Leh District faces multiple environmental and socioeconomic constraints, yet emerging technological and institutional innovations present opportunities for resilience and growth. The high-altitude, cold-arid climate restricts cultivation to a short growing season (May–September), with mono-cropping dominant across most blocks (Osmaston, 1994). Erratic snowfall, glacier retreat, and reduced irrigation water—reflecting a 50–80% rainfall deficit between 2013 and 2019—have intensified climatic stress (Gaur, 2025). Early frosts and flash floods further damage crops and accelerate soil erosion (Gaur *et al*., 2024). Land degradation affects about 24% of Leh's area, with frost shattering (36.21%) and vegetation degradation (3.04%) prominent in the Shyok sub-basin (Gaur, 2025). Skeletal, calcareous soils are highly erodible, reducing arable potential (Gupta and Arora, 2017; Gaur *et al*., 2024). Water scarcity compounds these pressures as 80% of small glaciers exhibit negative mass balance, while tourism-driven groundwater extraction requiring thousands of tankers daily worsens shortages and triggers field abandonment (Gaur and Goyal, 2022).

Livestock sustainability is undermined by a 40–45% fodder shortfall, particularly in Nyoma and Durbuk blocks, where shrinking cereal areas weaken the traditional crop-livestock system. Fodder availability averages 40–50% of requirements, relying mainly on crop residues, cultivated fodder, and grazing lands (Tewari *et al*., 2016). Urbanization and tourism have converted 8% of agricultural land between 1969 and 2017, with 4,900 new buildings added by 2023 (Gaur, 2025). Tourism, contributing 50% to Ladakh's GDP, has intensified land and water competition, diverting labor from agriculture. Limited post-harvest infrastructure, particularly for perishable crops like apricots, further restricts market access and value addition.

Amid these challenges, multiple opportunities are emerging. Protected cultivation technologies—such as greenhouses, trenches, and mulching—enable winter vegetable production, supporting local markets and defense needs. CAZRI, SKUAST-Kashmir, and DRDO have developed systems for sustaining crops like spinach, cabbage, and cauliflower even at –40°C (Gaur, 2025). High-value crops including *Rhodiola imbricata* and *Hippophae rhamnoides* (sea buckthorn) offer medicinal and commercial potential, with over 1,100 plant species—500 of them medicinal—identified for cultivation (Gaur, 2025). Oyster mushroom (*Dhingri*) production, using solar dryers for preservation, meets local nutritional needs and tourism demand (Gaur, 2025).

Value addition in horticulture through apricot and sea buckthorn processing into jams, juices, and nutraceuticals could reduce losses and raise incomes, especially if organized through Farmer Producer Organizations (FPO). Solar energy, with Ladakh's insolation of 7–7.5 $kWh/m^2/day$, supports greenhouse heating, irrigation, and crop drying (Santra, 2016). The revival of buckwheat (*Fagopyrum esculentum*), suited to degraded soils and short seasons, can strengthen food security and cultural continuity (LAHDC, 2012). Dairy expansion via improved breeds, water and fodder management, and manure recycling could boost the sector, which contributes 84.38% of livestock output (LAHDC, 2012). Floriculture, supported by greenhouse

technologies and local tourism markets, offers income diversification despite high airfreight constraints (LAHDC, 2012).

Integrating protected cultivation with solar energy, high-value crops, and value-addition initiatives could significantly enhance food self-reliance, income generation, and sustainability. If effectively scaled and supported institutionally, these innovations have the potential to transform Ladakh's fragile agricultural economy into a resilient and diversified system adapted to climatic and socioeconomic change.

Conclusions

Ladakh's agricultural system is undergoing a profound transition, driven largely by land use change, climate variability, and socioeconomic transformations. The cold-arid environment, once sustained by traditional agro-pastoral systems that balanced crop cultivation with livestock rearing, is now under increasing pressure from urban expansion, tourism, and shifting livelihoods. These forces have converted productive farmland into built-up areas, altered irrigation networks, and intensified competition for scarce water resources. As glacier retreat and declining snowfall reduce irrigation reliability, land degradation and soil erosion further limit the region's already constrained cultivable area, threatening long-term food security and ecological stability.

Yet, land use change in Ladakh also presents new opportunities for adaptation and sustainable growth. Protected cultivation, solar-powered irrigation, and the introduction of high-value crops such as sea buckthorn, medicinal plants, and buckwheat demonstrate how innovative land and resource management can enhance productivity within limited spaces. Similarly, integrating geospatial mapping and climate-resilient planning enables better monitoring of land transformation and informed policy decisions. However, technological advancement must align with traditional land stewardship practices that have evolved over centuries in harmony with the fragile environment.

Sustainable land use in Ladakh will depend on maintaining equilibrium between modernization and conservation—ensuring that economic expansion, tourism, and infrastructure growth do not undermine ecological integrity. Strengthening institutional frameworks, promoting community-based land management, and incentivizing sustainable agriculture are critical to reversing degradation and securing resilient livelihoods. Ultimately, the trajectory of land use change will determine whether Ladakh's future agriculture evolves as a model of adaptive sustainability or succumbs to the pressures of unbalanced development.

Statement

Hereby, all Authors consciously assure that for the manuscript (*Land Use Dynamics and Challenges in Leh District: A Temporal Analysis of Recent Three Decades*) the following is fulfilled:

- This material is the authors' own original work, which has not been previously published elsewhere.
- The paper is not currently being considered for publication elsewhere.
- The paper reflects the authors' own research and analysis in a truthful and complete manner.
- The paper properly credits the meaningful contributions of co-authors and co-researchers.
- The results are appropriately placed in the context of prior and existing research.
- All sources used are properly disclosed (correct citation).
- All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

The Authors, with the above statements and declare that this submission follows the policies of the Journal as outlined in the Guide for Authors and in the Ethical Statement.

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Conflicts of interest: The authors declare that they have no conflicts of interest.

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