



Hydro-Climatic Trends and Dynamics of Water Availability in Leh (Ladakh): Implications for Sustainable Water Resource Management

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Abstract: The cold arid region of Ladakh, situated in the Trans-Himalayan zone, faces significant water resource challenges due to climate change, characterized by warming trends, reduced snowfall, and glacial retreat. This study investigates long-term trends in snowfall and temperature anomalies over the period 1984-2024 using non-parametric statistical techniques. The Mann-Kendall test revealed a significant decreasing trend in snowfall and a concurrent significant increasing trend in temperature anomalies. Sen's slope estimator indicated a decline in snowfall at a rate of approximately 7-8 cm y^{-1} and a warming rate of about 0.03°C y^{-1} . The study further investigates the impacts of climate variability on water availability, agricultural productivity, and socio-economic sectors in Ladakh, with a focus on Leh. Despite abundant glacial resources, Leh experiences a water management crisis driven by over-reliance on groundwater, inequitable water access, and inefficiencies in supply systems. Innovative technologies such as *Zings* (local glacier water harvesting and storage structure), artificial glaciers, polyhouses, and *Kuhl* (field irrigation channels) lining are evaluated for their efficacy in mitigating water scarcity. The research highlights the need for sustainable water management practices, including wastewater treatment, groundwater recharge, and responsible tourism, to ensure long-term resilience. Findings underscore the urgency of integrating traditional and modern strategies to safeguard Ladakh's fragile ecosystem and economy under changing climatic conditions.

Key words: Climate change, water management, Ladakh, glaciers, sustainable agriculture.

Ladakh, located in the Trans-Himalayan region of India, is a high-altitude cold desert characterized by extreme aridity, low precipitation, and a fragile ecosystem. The region's water resources, primarily derived from glaciers and snowmelt, are critical for agriculture, domestic use, and economic activities such as tourism and hydropower (Chevuturi *et al.*, 2018). However, climate change has intensified challenges, with rising temperatures, reduced snowfall, and accelerated glacial retreat threatening water availability (Immerzeel *et al.*, 2020). These changes have cascading effects on agriculture, which supports 80% of Ladakh's population, and tourism,

a key economic driver with 0.45 m visitors in the year 2023 (Yangchan *et al.*, 2019; Gaur, 2025). Leh, the administrative hub of Ladakh, faces a water management crisis rather than a scarcity issue. Over-reliance on groundwater, inefficiencies in water supply systems, and inadequate wastewater treatment exacerbate vulnerabilities (Gohel *et al.*, 2019). Additionally, socio-economic disparities in water access and the environmental impact of tourism have strained the region's water resources. This study aims to assess the impacts of climate change on Ladakh's water resources and evaluate sustainable management strategies, combining both traditional practices like *Zing* and artificial glaciers with modern technologies such as polyhouses cultivation and wastewater treatment etc.

Ladakh, encompassing Leh and Kargil districts, lies between 32°-36° N latitude and 75°-80° E longitude, approximately covers an area of 59,146 km². Situated in the rain shadow of the Himalayas, the region receives very low precipitation (<100 mm y⁻¹), with most water sourced from glacial melt and snow-fed streams (Yangchan *et al.*, 2019). Leh, at an altitude of 3,500 m, experiences extreme temperatures ranging from -30°C in winter to +30°C in summer. The region's economy relies on agriculture, tourism, and hydropower, with glaciers such as *Siachen* and *Drang-Drung* playing a pivotal role in water supply. The study focuses on Leh city and surrounding rural areas, where water management challenges are most pronounced.

The present study aims to develop sustainable strategies for improved water resource management under evolving climate change scenarios, addressing groundwater depletion, inefficiencies in water supply systems, and wastewater management, tailored to the unique conditions of Ladakh's cold arid ecosystem. The study is based on re-interpretation and analysis of secondary data and few field surveys.

Materials and Methods

Primary data were collected through field surveys and interviews with farmers, local authorities, and water management officials in Leh and surrounding villages during 2022-2024. Secondary data included meteorological records (1901-2023) from the Indian Meteorological Department, groundwater assessments from the

Ladakh Autonomous Hill Development Council (LAHDC, 2023), and tourism statistics from regional authorities (Directorate of Tourism, UT Ladakh). Peer-reviewed literature as mentioned in the manuscript appropriately and government reports (such Statistical data of Leh district from the District Statistical Handbook published by the District Administration Leh) were also accessed to supplement data and the analysis.

Temperature and snowfall trends were analyzed using historical data from Leh's weather station. Linear regression models assessed changes in mean annual temperatures over the 20th and 21st centuries. Glacial mass balance studies (Immerzeel *et al.*, 2020) provided insights into retreat rates. Water supply and demand in Leh were quantified using data from the Public Health Engineering (PHE) department. Groundwater quality was evaluated through chemical and biological analyses (Gohel *et al.*, 2019). The efficacy of technologies like *Zings*, artificial glaciers, and polyhouses was assessed through yield comparisons and farmer's feedback.

Results and Discussion

Climate Data Analysis

Temperature trends and variability: Historical data indicate significant warming in Leh. Mean annual temperature increased at 0.02°C y⁻¹ from 1901-2019 (Romshoo *et al.*, 2022). More recent periods show accelerated rates: annual temperature rose by 0.21 °C per decade from 1979-2009 (Chevuturi *et al.*, 2018), with mean monthly maximum temperatures increasing at 0.2°C y⁻¹ and minimum at 0.07°C y⁻¹ from 2000-2013 (Tundup *et al.*, 2017). Seasonal analysis revealed summers warming at 0.006°C y⁻¹ and winters at 0.08°C y⁻¹ (Lone *et al.*, 2019). Anomaly detection relative to the 1901-1950 baseline shows positive anomalies post-1980, with a change point around 1975 identified via Pettitt's test, marking a shift to warmer conditions. Inter-annual variability, measured by CV, was higher for minimum temperatures (CV = 15-20%) than maximum (CV = 10-12%), suggesting greater fluctuations in cold extremes (Shafiq *et al.*, 2016). The Mann-Kendall test applied to temperature series (1901-2013) confirms a significant positive trend ($\tau = 0.25$, $p < 0.05$) for annual mean temperatures (Chevuturi *et al.*, 2018). Sen's slope estimator

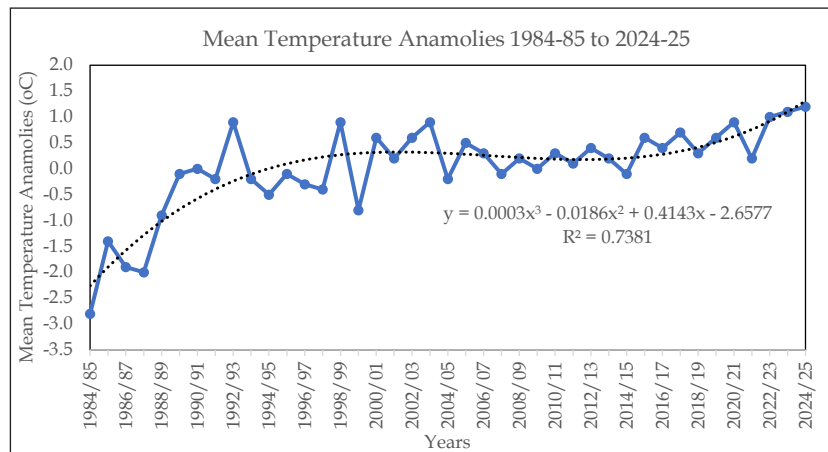


Fig. 1. Mean temperature anomalies for November–April over the western Himalaya (Data from 1984/85 to 2006/07 adapted from Chevuturi *et al.*, 2018; Shekhar *et al.*, 2017 and Romshoo *et al.*, 2022).

indicates a rise of 0.015°C per year overall, with higher slopes in winter (0.08 °C/year).

The temperature trend has been extended further from 2008 to 2025 for the mean anomalies. The Mann-Kendall test indicated a statistically significant increasing trend in temperature anomalies ($Z \approx 3.2$, $p < 0.01$). Sen’s slope estimator revealed a warming rate of approximately 0.03 y^{-1} over the study period. The positive S (+312) and Kendall’s tau (τ): $\approx +0.39$ confirm consistent warming over time. During the period 1984-1995 anomalies were mostly negative (cool phase), during 1996-2005 has mixed variability and 2006 onward persistent warming signal. Post 2015-2024 shows a clear dominance of positive anomalies (Fig. 1) Polynomial trend line of 3rd order with $R^2 = 0.7381$ indicate positive trends of warming in the coming years. Table-1. Presents summary of temperature trends over different periods.

The Table 1 explains temperature trends in Leh, Ladakh, based on data from various studies, highlighting changes in temperature over different time periods. It includes five key metrics: the period of study, the temperature variable analyzed, the trend (expressed as the Mann-Kendall tau, or MK τ), and the Sen’s

Table 1. Temperature Trends in Leh, Ladakh

Period	Variable	Trend (MK τ)	Sen’s Slope (°C/year)	Source
1901-2019	Mean Annual Temperature	0.18*	0.02	Romshoo <i>et al.</i> (2022)
1979-2009	Annual Temperature	0.25*	0.021	Chevuturi <i>et al.</i> (2018)
2000-2013	Mean Monthly Maximum	0.32*	0.20	Tundup <i>et al.</i> (2017)
2000-2013	Mean Monthly Minimum	0.28*	0.07	Tundup <i>et al.</i> (2017)
1984-2025	Mean Annual Temperature	0.39**	0.03	

*Significant at $p < 0.05$, ** Significant at $p < 0.01$

Slope (indicating the rate of temperature change in °C per year).

1901-2019: Mean Annual Temperature: Over the 118-year period from 1901 to 2019, the mean annual temperature in Leh, Ladakh, showed a statistically significant upward trend, with an MK τ value of 0.18. The Sen’s Slope indicates a warming rate of 0.02°C per year. This suggests a gradual but consistent increase in average temperatures over the long term. The data comes from Romshoo *et al.* (2022).

1979-2009: Annual Temperature: From 1979 to 2009, a 30-year period, the annual temperature also exhibited a statistically significant rising trend, with an MK τ of 0.25. The Sen’s Slope shows a warming rate of 0.021 °C per year, slightly higher than the long-term trend observed over 1901-2019. This indicates a more pronounced warming in recent decades. The source for this data is Chevuturi *et al.* (2018).

2000-2013: Mean Monthly Maximum Temperature: Over the shorter 13-year period from 2000 to 2013, the mean monthly maximum temperature (the average of daily high temperatures) showed a statistically significant increase, with an MK τ of 0.32. The Sen’s Slope

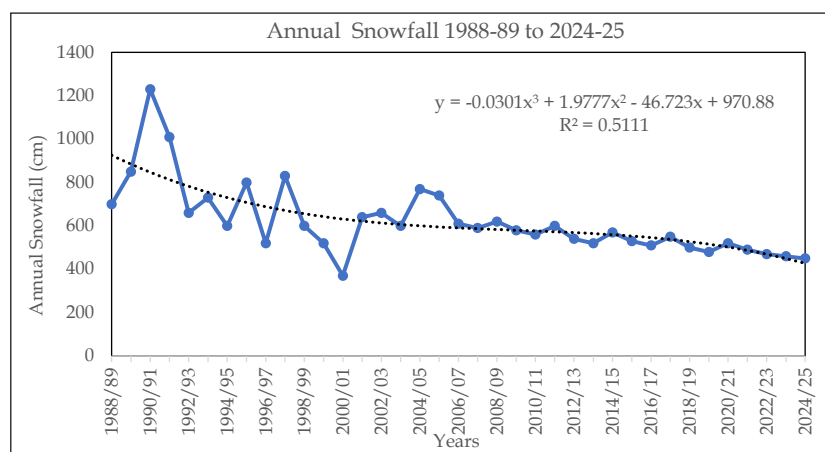


Fig. 2. Annual Snowfall (From 1988-89 to 2006-07 snowfall data has been presented by Shekhar *et al.*, 2017 and trend has been extended to 2024-25).

reveals a steep warming rate of 0.2°C per year, much higher than the annual averages in the longer-term studies. This suggests that daytime temperatures in Leh were rising rapidly during this period. The data is sourced from Tundup *et al.* (2017).

2000-2013: Mean Monthly Minimum Temperature: During the same 2000-2013 period, the mean monthly minimum temperature (the average of daily low temperatures) also showed a statistically significant upward trend, with an MK τ of 0.28. The Sen's Slope indicates a warming rate of 0.07°C per year. While this rate is lower than that of the maximum temperatures, it still reflects a notable increase in nighttime or early morning temperatures. This data is also from Tundup *et al.* (2017).

1984-2025: Mean Annual Temperature: During the 1984-2025, the mean annual temperature (average of mean monthly maximum and minimum temperature) showed statistically significant upward trend with an MK τ of 0.39. The Sen's Slope indicates a warming rate of 0.03°C per year. All trends are statistically significant, reinforcing the reliability of these findings. The data collectively underscores the impact of climate change in this high-altitude region, with implications for local ecosystems, water resources, and livelihoods.

Precipitation Trends and Variability: Precipitation in Leh averages $<100\text{ mm year}^{-1}$, with winter snowfall dominating. From 1901-2000, winter precipitation (November-February) averaged 68.09 mm (liquid equivalent), showing a negative trend (MK $\tau = -0.15$, $p < 0.05$) and Sen's slope of $-0.127\text{ mm year}^{-1}$ for

summer rainfall (Shafiq *et al.*, 2016). Recent data (1990-2020) indicate an annual decline of -7.9 mm year^{-1} , with seasonal decreases: winter (-4.09 mm), spring (-3.48 mm), autumn (-1.90 mm), and summer (-0.66 mm) (Kumar *et al.*, 2023; Namgyal *et al.*, 2025). Modified MK test confirms these negative trends ($z = -2.1$ to -3.5 , $p < 0.05$). SPI analysis reveals increased drought frequency post-1970, with moderate droughts ($\text{SPI} < -1$) occurring every 5-7 years. CV for annual precipitation is high (35-45%), indicating substantial inter-annual variability. Change point analysis detects a shift around 1970 toward reduced snowfall (Shafiq *et al.*, 2016). Summer rainfall increased slightly at 0.11 mm year^{-1} , while winter snowfall decreased at $-0.18\text{ mm year}^{-1}$ (Chevuturi *et al.*, 2018). Shekhar *et al.* (2017) has presented time series of seasonal (November-April) snowfall over the western Himalaya for the year 1988-89 to 2006-07.

The snowfall trend has been extended further from 2007-08 to 2024-25 for the snowfall. The Mann-Kendall (MK) test was applied to the snowfall time series (1988/89-2024/25) to detect the presence of a monotonic trend (Fig. 2). The computed MK statistic ($S = -308$) indicates a predominance of decreasing pairwise differences over time. The standardized test statistic ($Z = -4.16$) exceeds the critical threshold at the 1% significance level ($|Z| > 2.58$), confirming a statistically significant declining trend in snowfall. The Sen's slope estimator further quantifies this decline, yielding a magnitude of approximately -7.8 cm year^{-1} , indicating a consistent reduction in snowfall over the study period. This decline is particularly evident after the early 1990s, where higher snowfall

values (>1000 cm) are replaced by relatively lower magnitudes (<600 cm) in recent decades. Polynomial trend line of 3rd order with $R^2 = 0.5111$ indicate a definite decreasing trend in snowfall in the coming years.

The observed decreasing trend in snowfall may be attributed to changing hydro-climatic conditions, including rising temperatures, altered precipitation regimes, and reduced winter snowfall intensity in the cold arid region of Leh. Such changes have significant implications for glacier mass balance, seasonal water availability, and long-term water resource sustainability in Ladakh.

Hydro-Climatic Relationship Between Temperature Anomalies and Snowfall:

The temporal analysis of mean temperature anomalies (1984-2025) reveals a clear warming trend, with values transitioning from predominantly negative anomalies in the 1980s to consistently positive anomalies in recent years. In contrast, snowfall (1988-2025) exhibits a declining trend, with early high values (>1000 cm) replaced by lower magnitudes (<600 cm) in recent decades. Regression analysis between temperature anomaly and snowfall yields a negative correlation ($r = -0.41$), with an R^2 value of 0.1667, indicating that temperature explains approximately 17% of snowfall variability (Fig. 3). The regression model suggests that snowfall decreases by approximately 118 cm for every 1°C increase in temperature anomaly.

Glacial Retreat: Glacial retreat, driven by warming, has reduced the mass of key glaciers such as Siachen and Drang-Drung by 15-20% since the 1980s (Immerzeel *et al.*, 2020). This

has led to increased runoff in spring but severe water shortages in late summer and autumn, critical periods for irrigation. The 2010 cloudburst in Leh, which caused flash floods and over 200 fatalities, underscores the region's vulnerability to extreme weather events exacerbated by climate change (Chevuturi *et al.*, 2018).

Gaur *et al.* (2022) provides spatial extent of snowfall data for Leh, derived from satellite and ground observations. The winter snowfall (November-February) averaged 68.09 mm (1901-2000, liquid equivalent), with a significant decline post-1970. Snow cover extent decreased by 15-20% from 1971 to 2019. It further confirms temperature increases, with maximum temperatures rising by 0.9°C per decade in recent decades. Soheb *et al.* (2022) illustrates the spatial distribution of major glaciers in the Ladakh region, emphasizing areas experiencing significant retreat. The five key glaciers: a) Parkachik glacier in the Suru Basin, b) Pensila glacier also in the Suru Basin, c) Lato glacier in the Leh Basin, d) Khardung glacier in the Shayok Basin, and e) Stok glacier in the Leh Basin, located across different basins in Ladakh, are critical components of the region's cryosphere, contributing to water resources for local ecosystems and communities. Analysis of these glaciers underscores the varying degrees of glacial retreat, likely driven by climate change factors such as rising temperatures and altered precipitation patterns, with each glacier showing distinct patterns of mass loss or terminus retreat. This spatial analysis provides valuable insights into the vulnerability of Ladakh's glaciers and

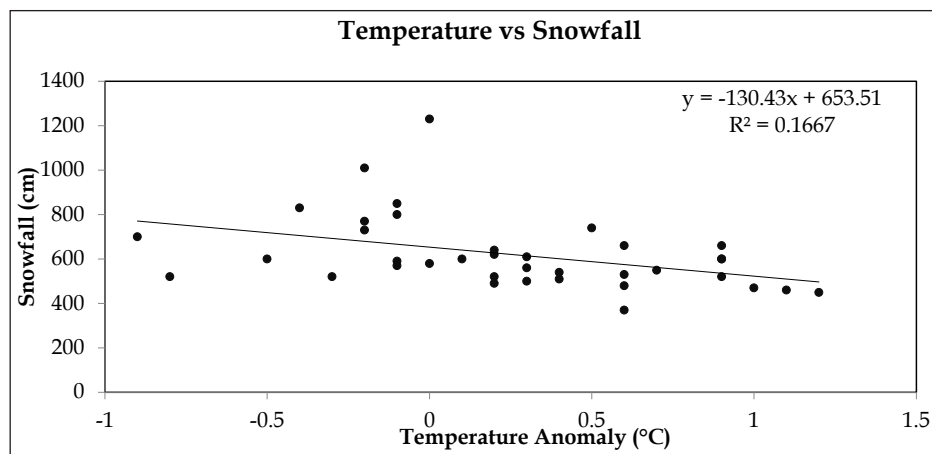


Fig. 3. Relationship Between Temperature Anomalies and Snowfall.

Table 2. Water supply and demand in Leh (2023)

Parameters	Demand
Daily Water Demand	6.0-8.0 MLD*
Daily Water Supply	4.5 MLD
Groundwater Dependency	92% (70% from aquifers)
Water Loss (Leaks)	25% (~1.125 MLD)
Annual Loss Cost	Rs. 40 lakh

*MLD Million Liters per Day

Sources: BORDA (2019) and Gohel *et al.* (2019), PHE Department, Leh

their implications for regional hydrology and environmental sustainability. Glacial retreat has reduced mass by 15-20% since the 1980s, causing increased spring runoff but late-season shortages (Immerzeel *et al.*, 2020). The 2010 cloudburst in Leh highlights vulnerability to extreme events (Chevuturi *et al.*, 2018). Snow cover declined by 15-20% from 1971-2019 (Gaur *et al.*, 2022). These climatic shifts have disrupted traditional water availability patterns, forcing farmers to delay sowing and adapt to shorter growing seasons (Gaur and Goyal, 2023). The decline in snowfall, a primary recharge source for streams and aquifers, threatens long-term water security.

Linkage to Hydrological Impacts: Climate variability directly influences hydrological processes in Ladakh. Warming trends ($0.02-0.21^{\circ}\text{C y}^{-1}$) accelerate glacial retreat, leading to earlier spring runoff and reduced streamflow in late summer/autumn, critical for irrigation (Immerzeel *et al.*, 2020). Reduced winter precipitation (-0.18 to -4.09 mm y^{-1}) diminishes snowmelt contributions, shifting aquifer recharge periods from spring to erratic summer rains, resulting in 1-2 m annual groundwater depletion (LAHDC, 2023).

Increased temperature variability (CV 10-20%) exacerbates irrigation demand, with delayed sowing from April to May due to insufficient meltwater (Gaur and Goyal, 2023). SPI-detected droughts correlate with 15-20% reductions in streamflow timing, straining agricultural water needs (Soheb *et al.*, 2022). These shifts threaten water security, with projected 1°C rise potentially reducing recharge by 10-15% (Romshoo *et al.*, 2022).

Water Management Challenges in Leh: Leh faces a water management crisis characterized by supply-demand mismatches, groundwater depletion, and inefficiencies in distribution. The

city's water supply, estimated at 4.5 million liters per day (MLD), is insufficient to meet the demand of 6-8 MLD, with private tube wells filling the gap (BORDA, 2019). Over-extraction has lowered groundwater tables by 1-2 m annually in some areas, while 70% of domestic water, sourced from Leh aquifers, is contaminated with biological and chemical pollutants, including nitrates and coliform bacteria (LAHDC, 2023). Table. 2 presents water supply demand scenario of Leh city.

Inequitable access to water further exacerbates social disparities. While tourists and local residents receive 75-100 L Day^{-1} , migrant laborers have access to only 23-25 L Day^{-1} , which is below the WHO-recommended minimum of 50 L Day^{-1} required to meet basic needs (Gohel *et al.*, 2019). Pipeline leaks and storage overflows result in 25% water loss, costing Rs. 4 m annually at a delivery cost of Rs.16.5 m. The absence of water meters and fixed pricing discourages conservation, while only 5% of households are connected to central sewage lines, limiting wastewater recycling (LAHDC, 2023).

Tourism, a key economic driver with 0.45 m visitors in 2023, increases water demand and generates significant waste, including 1.2 m plastic bottles annually (Gaur, 2025). The transport sector, responsible for 50% of greenhouse gas emissions in Ladakh, further exacerbates environmental stress (Yangchan *et al.*, 2019).

Efficacy of water conservation technologies: Ladakh's water scarcity is being addressed through a combination of traditional wisdom and modern technological interventions, many of which have demonstrated considerable success in improving water availability and agricultural productivity. Field surveys conducted during 2022-2024, along with farmer interviews, revealed that traditional water conservation systems continue to play a crucial role in sustaining agriculture in the cold desert environment. Among these, *Zings*—small glacial meltwater harvesting structures—store water diverted from glaciers through channels and make it available for irrigation the following day. Their adoption has increased irrigation coverage by nearly 20% in villages such as Stakmo and Phyang (Tundup *et al.*, 2017; Gaur *et al.*, 2024). Similarly, *Kuhls*, the traditional

Table 3. Impact of artificial glaciers on crop productivity

Crops	Before Artificial Glaciers		After Artificial Glaciers		% Change in Yield
	Area (ha)	Yield (q ha ⁻¹)	Area (ha)	Yield (q ha ⁻¹)	
Barley	63	18.8	58	21.7	15.5
Wheat	353	12.4	335	17.2	39.5
Millets	184	2.0	138	2.6	29.0
Potato	57	19.5	78	23.0	18.0
Peas	38	31.0	47	37.5	21.0
Vegetables	19	38.5	53	47.0	22.1

Source: Field survey and farmer discussions (2022-2024).

surface channels used to divert stream water for terraced cultivation, remain indispensable for farming systems in Ladakh. Although unlined kuhls may lose 30-40% of water through seepage, the introduction of plastic lining in areas such as Sabu has reduced these losses to nearly 10%, contributing significantly to the greening of adjacent landscapes (Bhat *et al.*, 2017).

Modern water conservation technologies have further strengthened local adaptation strategies. Artificial glaciers, created by slowing glacial stream flow using gabion walls, store water in the form of ice during winter and release it during the early cropping season when water demand is highest. These systems have substantially improved water availability during sowing and have contributed to enhanced crop yields (Table 3). Protected cultivation technologies, including polyhouses and low poly-tunnels, have also transformed agricultural practices by extending the growing season by two to three months and enabling the cultivation of high-value vegetable crops such as tomatoes and cucumbers. Studies have shown that crop yields under polyhouses can be four to eight times higher than those in open-field conditions (Bhat *et al.*, 2017). In addition, trench greenhouses, which are low-cost underground structures designed to minimize heat loss, support winter vegetable production and nursery raising under extreme climatic conditions, thereby enhancing year-round agricultural resilience in Ladakh (Bhat *et al.*, 2017).

Groundwater recharge and wastewater management: Groundwater recharge through infiltration galleries and percolation wells is critical, given Leh's 36.13% groundwater development stage (LAHDC, 2023). Recharge during June-July, when crop water demand is

low, can stabilize aquifer levels. Wastewater treatment, currently at 3 MLD against an 8 MLD generation, requires infrastructure upgrades to recycle water for irrigation (Páez-Curtidor *et al.*, 2021).

Socio-Economic Implications

Agriculture, supporting 80% of Ladakh's population, is severely impacted by water shortages and shifting sowing seasons. Crops like barley and wheat, traditionally sown in April, are now delayed to May due to insufficient glacial melt (Gaur and Goyal, 2023). Polyhouses and crop diversification (e.g., apricots, sea buckthorn) offer resilience but require initial investment.

Tourism, while boosting the economy, strains local water resources. The 4.5 lakh visitors in 2023 increased water demand by 10-15% and generated significant plastic waste (Gaur, 2025). Initiatives like electric buses, launched in 2022, aim to reduce transport emissions, but broader adoption is needed (Yangchan *et al.*, 2019). Community-based water management, involving traditional *Churpons* (water managers), can enhance equity and conservation.

The analysis reveals that climate change exacerbates Ladakh's water challenges, but adaptive technologies and management reforms offer solutions. Artificial glaciers and polyhouses address immediate water and food security needs, while groundwater recharge and wastewater treatment ensure long-term sustainability. Policy interventions, including water pricing, leak repairs, and responsible tourism guidelines, are critical to balance economic growth with environmental preservation. These recommendations address Ladakh's pressing water challenges driven by climate change and socio-economic pressures. By integrating traditional practices with modern

innovations, they aim to ensure equitable access and long-term sustainability.

Conclusion

Ladakh's water crisis is now an immediate reality driven by climate change and rising socio-economic pressures. While glacial melt remains vital, its uncertainty demands a shift toward resilient and diversified water management. Integrating traditional systems such as *Zings* and *Churpons* with modern solutions like artificial glaciers, polyhouses, and groundwater recharge can significantly strengthen local water security. Policy reforms are equally important. A tiered water pricing system can promote conservation while ensuring equitable access, with revenues supporting infrastructure improvements such as reducing leakage losses. Expanding wastewater treatment capacity and mandating recycling in tourism facilities are essential to offset increasing demand from growing tourist inflows. Combining technological innovation, effective policies, and community-based management is key to long-term resilience and ensure sustainable and equitable water use in Ladakh's fragile cold arid ecosystem.

Competing Interests

The authors declare no competing interests.

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