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Agricultural water deficit and wastewater reuse potential in Patiala district, Punjab

Sanjoy Gorai[1*], Manoj Kumar[2]

[1] Assistant Professor, Department of Chemistry and Environmental Sustainability, School of Sciences, IILM University, Greater Noida, India

[2] Assistant Professor, Department of Mathematics, School of Sciences, IILM University, Greater Noida, India

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Corresponding author:
sanjoy.gorai@iilm.edu

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Abstract

The study examines future rainfall patterns, runoff generation, and net water deficits in the Patiala district of Punjab for 2024, 2030, 2035, and 2040, with a particular focus on agricultural water demand. Projections reveal a steady rise in average annual rainfall, increasing from 735.99 mm in 2024 to 757.27 mm by 2040, which translates into higher runoff, from 2.37 to 2.44 billion m^3. Despite this positive trend, water scarcity remains a pressing concern. Under minimum irrigation consumption scenarios, the net water deficit declines moderately from 0.252 billion m^3 (9.61%) in 2024 to 0.183 billion m^3 (6.99%) in 2040, suggesting slight relief. However, under maximum consumption scenarios, the deficit persists at alarming levels, decreasing only marginally from 1.57 billion m^3 (39.93%) to 1.51 billion m^3 (38.19%) over the same period. These results indicate that even with marginal increases in rainfall, rapidly growing agricultural demand will continue to place severe pressure on water resources. The study emphasizes the urgent need for sustainable water management, including efficient irrigation systems, groundwater recharge, wastewater reuse, and rainwater harvesting. Reuse of wastewater can fulfil up to 33.2% of the deficit from rainfall. Therefore, the study suggests reuse of the wastewater generated from the rural area of the study after some basic treatments which will reduce the load on groundwater as well as reliance on rainfall.

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Introduction

Agriculture is the foundation of human survival, providing essential food, fodder, clothing, and medicinal resources while ensuring food security. It is also central to the economy, particularly in rural regions where it supports livelihoods, generates employment, and supplies raw materials to key industries such as textiles, sugar, and food processing. Moreover, agriculture significantly contributes to Gross Domestic Product (GDP) and international trade. Beyond its economic and subsistence value, agriculture plays a crucial role in sustainable development. Eco-friendly practices help conserve soil, water, and biodiversity, reduce environmental degradation, and enhance resilience to climate change. By fostering long-term productivity, poverty reduction, and natural resource conservation, agriculture directly advances global Sustainable Development Goals (SDGs) (Shang & Xie, 2024).

Water is vital for crop growth, supporting germination, nutrient uptake, and photosynthesis, and directly influencing yield and quality. Agriculture consumes about 70–80% of global freshwater resources (Rosegrant et al., 2009). Crop water requirements vary by crop and conditions, with rice needing about 1200–1500 mm and wheat about 450–650 mm per season. Given the sector's vast consumption, efficient water management practices such as drip irrigation, sprinklers, mulching, and rainwater harvesting are essential to prevent overuse, sustain groundwater levels, and secure long-term food production.

Water scarcity, particularly linked to rainfall deficiency, poses a severe challenge to agriculture. Reduced rainfall lowers soil moisture, groundwater recharge, and canal flows, thereby limiting irrigation. This leads to water stress, poor germination, stunted crop growth, and yield losses. Rainfed regions are especially vulnerable, as even short dry spells may cause crop failure (Rockström et al., 2003). Prolonged deficits also drive excessive groundwater extraction, exacerbating depletion and soil degradation. Ultimately, water scarcity undermines food security and farmer livelihoods. Coping strategies include rainwater harvesting, drought-resistant crops, efficient irrigation methods, and integrated water management.

To address rainfall deficits, farmers must adopt alternative water sources. Rainwater harvesting in ponds, tanks, or check dams provides supplementary irrigation, while groundwater recharge structures like percolation pits and recharge wells help replenish aquifers. Modern irrigation systems such as drip and sprinklers minimize evaporation losses and deliver water efficiently to plant roots (Ray & Majumder, 2024). Another promising solution is the use of treated wastewater, which offers a reliable year-round irrigation source. Rich in nutrients such as nitrogen, phosphorus, and potassium, it reduces dependence on chemical fertilizers (Jaramillo & Restrepo, 2017). Its reuse lowers farming costs, improves soil fertility, prevents water pollution, and strengthens environmental sustainability, making it a crucial tool for climate-resilient agriculture.

Punjab, popularly known as the "Granary" or "Breadbasket of India", illustrates agriculture's importance (Bonfanti, 2025). It contributes a significant share of wheat and rice to India's food grain pool. The state spearheaded the Green Revolution, becoming a hub of mechanized and irrigated high-yield farming. Patiala district reflects this agricultural legacy, dominated by intensive cereal farming, horticulture, and emerging diversification. However, challenges such as groundwater depletion, straw management, pest outbreaks, and resistance to ecological innovations highlight the urgency for sustainable solutions. Against this backdrop, the present study aims to:

- To assess the status of water resources in Patiala district in relation to agricultural water demand.
- To analyze long-term rainfall trends.
- To estimate irrigation water requirements for major crops cultivated in the study area.
- To compare crop water requirements with rainfall contribution to identify irrigation water deficits.

- To quantify wastewater generation in the district.
- To evaluate the feasibility of using treated wastewater as an alternative source for irrigation.
- To examine existing and low-cost wastewater treatment systems and propose sustainable water management strategies for agriculture.

The paper begins with an Introduction, followed by a detailed Materials and Methods section that describes the study area and the approach adopted for rainfall trend analysis. The Results and Discussion section presents an assessment of average annual rainfall, examines rainfall trends, and discusses projected rainfall patterns. It further evaluates irrigation water demand, irrigation water deficiency, and wastewater generation, along with an analysis of water demand and supply. The study also assesses the quality of treated wastewater for irrigation and reviews the availability of wastewater treatment facilities in the Patiala region. The paper concludes with a Conclusions section summarizing the key findings and implications of the study.

Materials and Methods

Study Area

Patiala district is located in the southeastern part of Punjab and is one of the state's most prominent districts, both historically and agriculturally. The district covers an area of about 3,218 km² and has Patiala city as its administrative headquarters. Geographically, it lies in the fertile Indo-Gangetic plain, with alluvial soils that make it highly suitable for agriculture. Patiala district, with a population of 1.9 million (Population Census, 2011), resulting in a density of 570 persons/km². Patiala district spans approximately 3,222 km², of which around 80-81% is cultivable land. Main cropping systems include traditional rotations like rice-wheat, as well as combinations such as rice-potato-sunflower, basmati rice-wheat, maize-wheat, and maize-lentil/taramira. Figure 1 shows the location of Patiala district in India as well as Punjab Map.

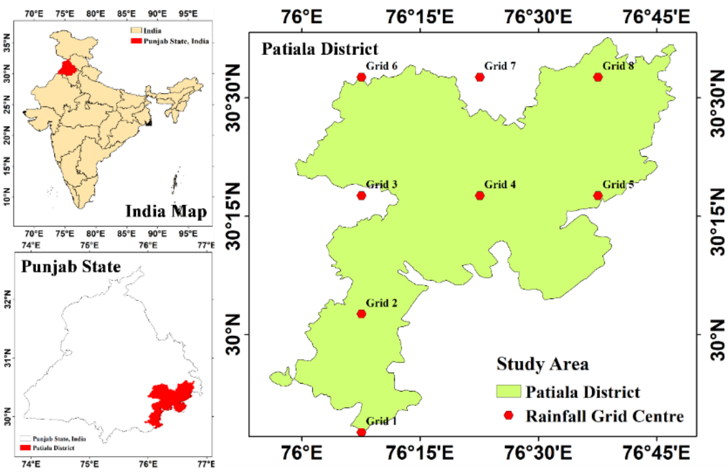

Figure 1. Study Area of Patiala District shown in Punjab map and Punjab map shown in India map.

Rainfall Trend Analysis

The trend of rainfall and temperature has been analysed using Innovative trend analysis. The obtained results were validated using Mann-Kendall test and Sen Slope estimator.

Innovative Trend Analysis (ITA): The ITA slope (S) i.e., magnitude change per time period has been calculated using Eq. (1)

$$S = \frac{2(\overline{y_2} - \overline{y_1})}{n} \tag{1}$$

where, $\overline{y_1}$ is the arithmetic mean of the first halves of the dataset, $\overline{y_2}$ is the arithmetic mean of the second halves of the dataset and n is the length of Dataset. The significance of the slope value is assessed using hypothesis testing, which includes the null and alternative hypotheses (Şen, 2017). The calculation of significant trend is based on the confidence limit as discussed by Şen, 2017. It is considered as an increasing (decreasing) trend if the trend slope exceeds the upper (lower) confidence level (Esit, 2023).

Mann-Kendall test and Sen-slope estimator: The Mann-Kendall test is used in this study to validate trend analysis results from the ITA methodology. It is widely applied in hydrometeorological trend analysis (Wu & Qian, 2017). The Z value defines the data trend, with significance determined by null hypothesis acceptance at a 5% level (Jain et al., 2013). The Sen Slope estimator analyzes the trend slope, representing the rate of change per unit time (Jain et al., 2013).

Result and Discussion

Average Annual Rainfall

The annual rainfall data (grided 0.25°) of the Patiala district has been collected from Indian Meteorological Department for the period of 1901-2024 Pai et al. (2014). Figure 1 (Patiala District Map) shows the grid centre for the data was used. The data is extracted using ArcGIS and converted netcdf data to excel file based on the grid. The rainfall data is analysed and calculated average annual rainfall, rainfall trend analysis and projected rainfall for next 20 years based on the trend slope.

The rainfall analysis across the eight grids reveals marked spatial variability in both magnitude and stability. Table 1 shows the descriptive statistics of the annual rainfall in the Patiala district of Punjab in India. Rainfall across the grids shows clear spatial variation, with minimum values from 196.7 mm (Grid 2) to 433.7 mm (Grid 8) and maximums from 1181.7 mm (Grid 1) to 1732.0 mm (Grid 8). Average rainfall rises from 503.2 mm (Grid 1) to 944.4 mm (Grid 8), with variability (25.8-36.4%) higher in wetter grids. Grids 1-2 face drought risk, while Grids 5-8 support surplus water and recharge. Figure 2 shows the spatial map of the average rainfall of Patiala district. The rainfall distribution over the basin shows that the rainfall is decreases in the south-west direction from north-east direction. Overall, the average annual rainfall of the Patiala district is 735.9mm.

Table 1. Grid-wise rainfall descriptive statistics of Patiala District, Punjab, India

Location	Minimum (mm)	Maximum (mm)	Average Rainfall (mm)	Standard Deviation (mm)	Coefficient of Variance (%)
Grid 1	215.6	1181.7	503.2	172.1	34.2
Grid 2	196.7	1395.0	542.2	197.1	36.4
Grid 3	222.0	1537.2	639.5	213.4	33.4
Grid 4	363.1	1462.7	772.0	223.6	29.0
Grid 5	378.3	1628.9	889.6	247.1	27.8
Grid 6	210.7	1617.0	686.4	219.2	31.9
Grid 7	274.0	1537.7	783.8	225.5	28.8
Grid 8	433.7	1732.0	944.4	243.2	25.8

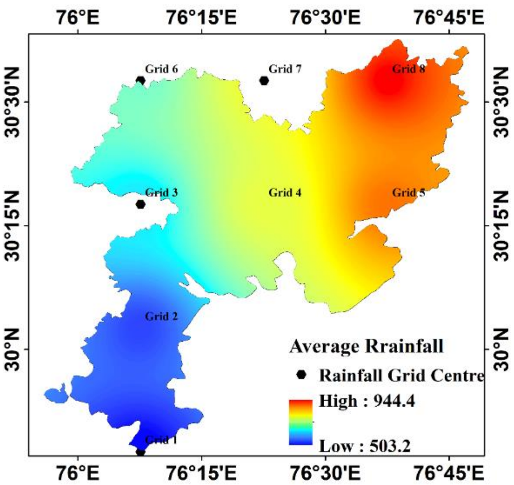

Figure 2. Spatial map of average rainfall of Patiala District, Punjab, India

Rainfall Trend Analysis

The combined results of the Mann-Kendall Test (MKT) and Innovative Trend Analysis (ITA) reveal predominantly positive rainfall trends across eight grids, though with spatial variability. Figure 3 shows the spatial map of the ITA slope and Sen's Slope of Patiala district of Punjab, India. Grid 1 shows a significant negative slope (-0.1642 mm/year), indicating declining rainfall and potential vulnerability to water stress. In contrast, Grids 2-8 display significant positive trends, with the strongest increases in Grid 4 (2.3051 mm/year) and Grid 5 (2.1802 mm/year), suggesting enhanced water availability. Moderate increases are noted in Grids 3, 6, 7, and 8 (0.58-1.62 mm/year), while Grid 2 shows a smaller yet significant rise (0.4933 mm/year). On average, the basin records an overall positive slope of 1.33 mm/year, highlighting increased rainfall potential but also the need to manage localized declines.

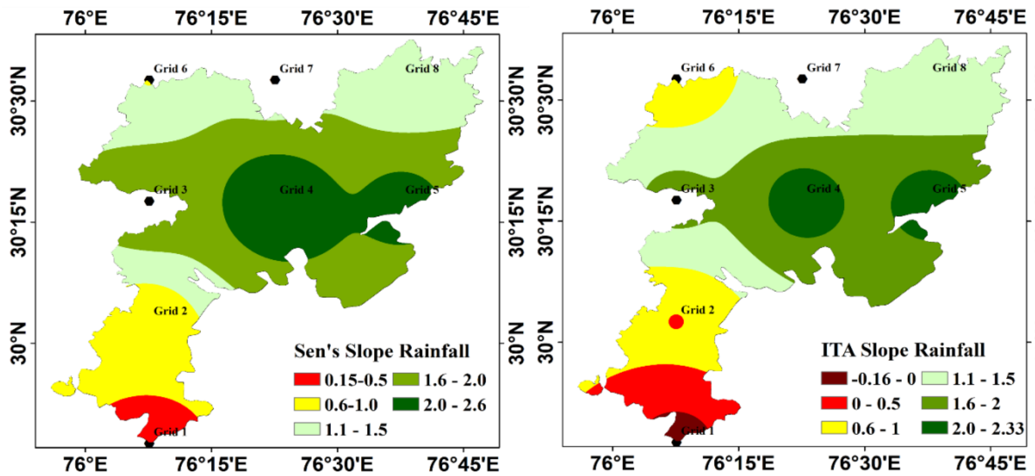

Figure 3. Spatial map of trend slope (ITA Slope and Sen's Slope) of Patiala District, Punjab, India

Projected rainfall

The rainfall has been projected simply using the slope of the ITA trend for the year of 2030, 2035 and 2040. The average annual rainfall of the district is 735.99mm whereas the overall trend is increasing at the rate of 1.33mm/year. The rainfall is projected to be 743.97mm in 2030, 750.62mm in 2035 and 757.27mm in 2040.

Irrigation water Demand

As per the Central Ground Water Board (CGWB) report, all eight blocks of Patiala district, Punjab, fall under the category of over-exploited zones (CGWB, 2018). Continuous extraction of groundwater by farmers has led to a steady decline in water levels across the district. With decreasing rainfall trends and the lack of an effective rainwater management strategy, farmers remain heavily dependent on groundwater to meet their agricultural irrigation needs. In this context, a water balance chart has been developed for Patiala district, taking into account the prevailing rainfall pattern and agricultural practices.

The data regarding the cropping pattern of this district were collected from Department of Agriculture, Government of Punjab (Punjab Agricultural University, 2017). The water requirement of different crops has been collected from (Food and Agriculture Organization, 1985; Praharaj et al., 2016). Table 2 presents the total cultivated area under various crops along with their corresponding water requirements. From the analysis, it is evident that paddy and wheat dominate the cropping pattern in the district and demand the highest amount of water. The details of different crops grown, their respective areas, and water requirements are provided in Table 2. Based on this, the minimum and maximum water demand for the district has been estimated. The minimum requirement of water for irrigation is 2.623 billion m³ and maximum requirement of water for irrigation is 3.947 billion m³.

Irrigation Water Deficiency

Figure 4 compares agricultural water demand with rainwater availability for 2024, 2030, 2035, and 2040. The runoff generation is calculated using simple multiplication of rainfall with surface area assuming no losses, so that the deficiency can be seen even after taking whole amount. Rainfall is projected to rise slightly from 735.99 mm to 757.27 mm, increasing runoff from 2.37 to 2.44 billion m³. Despite this, the district faces persistent net water deficiency. Under minimum consumption, the deficit decreases from 0.252 to 0.183 billion m³ (9.61%-6.99%), offering limited relief. Under maximum consumption, the deficit remains severe, only reducing from 1.57 to 1.51 billion m³ (39.93%-38.19%). This underscores the urgent need for water conservation, efficient irrigation, wastewater reuse, and recharge strategies to ensure long-term sustainability.

Table 2. Irrigation water demand calculation of Patiala District, Punjab, India

Sr. No	Crop Name	Total area sown	Water requirement	Type of crop	Minimum water demand	Maximum water demand
		(hectare)	(mm)		m^3	m^3
1	Paddy	269110	450-700	Kharif	1,210,995,000	1,883,770,000
2	Wheat	267430	450-650	Rabi	1203435000	1738295000
3	Fodder	26890	450-600	Kharif, Rabi	121005000	174785000
4	Vegetables	5080	300-500	Kharif, Rabi	15240000	25400000
5	Fruit Crops	4600	500-1000	Kharif, Rabi	23000000	46000000
6	Sugarcane	1950	1500-2500	Kharif	29250000	48750000
7	Peas	1720	350-500	Rabi	6020000	8600000
8	Potato	1430	500-700	Rabi	7150000	10010000
9	Mustard	810	240-400	Rabi	1944000	3240000
10	barley	620	450-650	Rabi	2790000	4030000
11	Maize	300	500-800	Kharif	1500000	2400000
12	Cotton	150	700-1300	Kharif	1050000	1950000
13	Moong	40	200-500	Kharif	80000	200000
14	Arhar	10	200-500	Kharif	20000	50000
15	Gram	10	200-500	Rabi	20000	50000
				Total	**2,623,499,000**	**3,947,530,000**

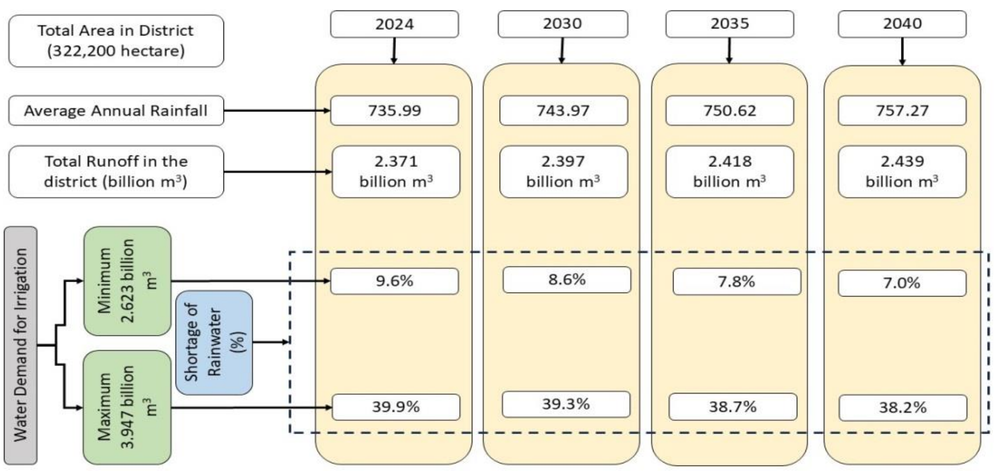

Figure 4. Comparison of water requirements for crops with current and future scenario using average run-off data in Patiala district

Wastewater generation

According to the NITI Aayog report (2022), per capita wastewater generation in India ranges between 10-25 m³/year, while CPCB studies estimate around 98 lpcd. For this analysis, 90 lpcd has been assumed for Patiala district. Spatial distribution of population density (Census 2011) and corresponding wastewater generation highlight pronounced regional disparities. Population density as shown in Figure 5(a) varies from 0 to 10,831 persons/km², with a cumulative population of 1.85 million. The district records a mean density of 409.52 persons/km², but a high standard deviation (851.23) indicates stark contrasts between sparsely and densely populated zones.

Wastewater generation, derived from population distribution, similarly reflects wide variation. Figure 5(b) shows the waste water generation from the district, values range from 0 to 355,808.63 m³/year, with a total of 60.92 million m³/year. The mean wastewater generation is 13,502.70 m³/year, though the large standard deviation (28,010.92) underscores spatial heterogeneity. Overall, wastewater production in Patiala is concentrated in high-density urban clusters, while large rural tracts remain minor contributors, emphasizing the need for localized management strategies.

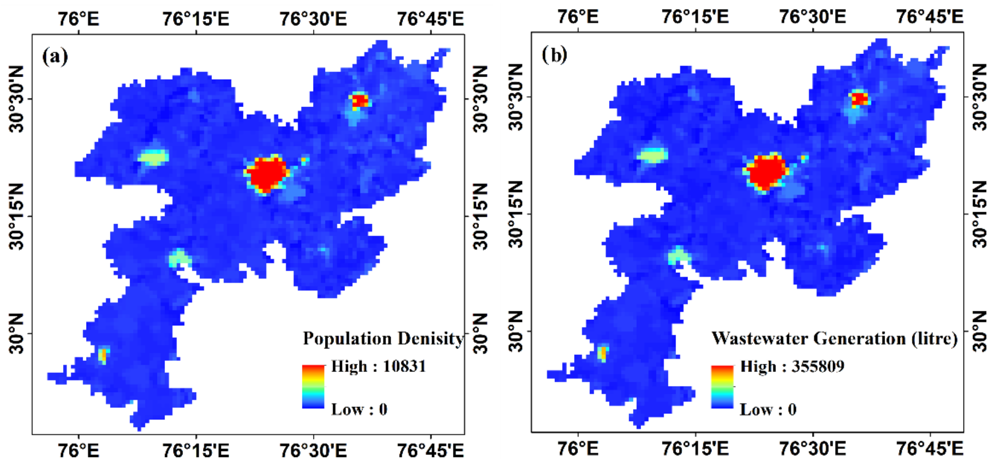

Figure 5 (a) Population Density (person/sq. km) and **(b)** wastewater generation (litre/sq.km) of Patiala district

Water Demand and Supply

The treated wastewater can be utilised as a source of irrigation which will reduce the water demand from groundwater as well as canal sources. The water balance assessment for Patiala district indicates gradual improvements in resource availability and wastewater utilisation over the period 2024-2040. The district, with a fixed geographical area of 322,200 hectares, records a modest rise in average annual rainfall from 736 mm in 2024 to 757 mm in 2040, which contributes to an increase in runoff generation from 2,371 MCM in 2024 to 2,440 MCM in 2040.

The water deficiency was calculated as:

$$\frac{Irrigation\ Water\ Demand - Waste\ Water\ Geneation}{Irrigation\ Water\ Demand} \times 100 \quad (2)$$

The net water deficiency for minimum consumption decreases from 252 MCM in 2024 to 184 MCM in 2040, while for maximum consumption it falls from 15,762 MCM to 15,076 MCM during the same period. In percentage terms, deficiency for minimum needs reduces from 9.6% to 7.0%, while for maximum needs it decreases slightly from 39.9% to 38.2%. The total population remains constant at 1.896 million persons, generating wastewater at 90 lpcd, which amounts to 623 MCM per year. With wastewater reuse, consumption reduction under minimum needs improves from 24.7% in 2024 to 33.9% in 2040, whereas under maximum needs it improves only slightly, from 3.95% to 4.13%. As a result, the revised net consumption under minimum requirements decreases from 1,899 MCM in

2024 to 1,213 MCM in 2040. Similarly, under maximum requirements it reduces from 15,139 MCM to 14,453 MCM during the same period. Overall, the findings highlight that wastewater reuse significantly offsets water stress under minimum consumption scenarios, while under maximum consumption the relief is comparatively marginal. Thus, integrated management of rainfall runoff, efficient utilisation, and wastewater recycling emerges as a vital strategy for sustaining water resources in Patiala district.

Treated Wastewater Quality for irrigation

The quality of treated wastewater is the important factor for its reuse. Table 3 shows the list of parameters and their standard limit for its reuse in agriculture.

Table 3. Quality standard of treated wastewater for its reuse in agriculture (Jamshidzadeh & Tavangari Barzi, 2020)

Sr No	Parameter	Unit	Standard Limit	Sr No	Parameter	Unit	Standard Limit
1	BOD_5	mg/l	100	10	Nitrate (NO_3)	mg/l	5
2	Boron (B)	mg/l	0.7	11	pH	----	6 - 8.5
3	Calcium	mg/l	200	12	Phosphate	mg/l	10
4	COD	mg/l	200	13	SAR	%	3
5	Chloride	mg/l	142	14	Sodium	mg/l	70
6	EC	µS/cm	700	15	Total Coliforms	MPN/100ml	1000
7	Fecal Coliforms	MPN/100ml	400	16	TDS	mg/l	450
8	Magnesium	mg/l	100	17	TSS	mg/l	30
9	Manganese	mg/l	0.2	18	Turbidity	NTU	50

Available Wastewater Treatment in the Patiala District

Wastewater can be a valuable resource for irrigation when properly treated. In Patiala district, both urban and rural areas have adopted different wastewater management systems. Currently, the district has 123.5 MLD operational STP capacity, with another 25 MLD under construction /approval, making a total of 148.5 MLD available for irrigation. Most urban STPs use Sequencing Batch Reactor (SBR) technology, which is efficient in nutrient removal and widely applied in India.

While urban wastewater is treated through STPs, rural wastewater is primarily stored in village ponds. Patiala district has 1,340 ponds covering 1,826.76 acres, out of which 239 ponds are already used for irrigation, while 1,101 ponds remain untapped. These are generally raw earthen ponds, though some are equipped with treatment models: 1 STP pond, 5 Waste Stabilization Ponds (WSPs), 3 Thapar Model ponds, and 12 Seechewal Model ponds. Such decentralized, low-cost systems offer sustainable treatment for rural wastewater.

Waste Stabilization Ponds (WSPs) are large, shallow basins where natural processes—biodegradation, photosynthesis, and solar disinfection—treat wastewater. Typically arranged in anaerobic, facultative, and aerobic ponds, WSPs reduce organic matter and pathogens through microbial and algal activity (Dwivedi & Dwivedi, 2022; Nagarajan et al., 2019). Anaerobic ponds settle solids and reduce organic load, facultative ponds enable bacteria-algae symbiosis for further decomposition, and aerobic ponds provide final stabilization and pathogen removal. The BOD/COD removal efficiency using WSP is up to 90% (Tilley et al., 2014). WSPs are cost-effective, energy-efficient, and suitable for irrigation reuse, though they require large land areas and proper management of algal biomass.

The Thapar Model, developed under the Swachh Bharat Mission (Grameen), is a modified WSP system tailored for rural India (Swachh Bharat Mission (Grameen), 2021). It involves four stages: (i) screening and skimming to remove solids, (ii) a stabilization tank for initial settling, (iii) an oxidation pond where algae release oxygen to aid bacterial decomposition, and (iv) a maturation/storage pond for polishing and storing treated effluent. The BOD/COD removal efficiency of Thapar Model is up to 85 - 90% (Gorai et al., 2025). Its simplicity, reliance on natural processes, and low cost make it well-suited to resource-constrained rural communities.

The Seechewal Model of Greywater Management (GWM), pioneered in Punjab, uses a three-well system followed by a renovated pond (Swachh Bharat Mission (Grameen), 2023). Greywater first passes through screening chambers to remove large impurities, then flows sequentially through three wells where sedimentation, grease removal, and clarification occur. The BOD/COD removal efficiency of Seechewal greywater model is up to 80 - 90% (Gorai et al., 2025). The treated water is finally stored in a village pond for reuse in irrigation. This model reduces dependence on borewells and promotes sustainable water use.

Together, these treatment approaches, including urban STPs and rural pond-based systems, provide the Patiala district with a sustainable framework for wastewater reuse in agriculture, contributing to both water conservation and environmental management.

Conclusions

Agriculture remains the backbone of livelihoods, food security, and economic stability in Patiala district, but its sustainability is increasingly threatened by rainfall variability and groundwater depletion. The analysis highlights that while rainfall provides a substantial share of water, it alone cannot meet the growing irrigation demand, resulting in persistent deficits. Efficient irrigation, rainwater harvesting, groundwater recharge, and adoption of drought-resilient practices are therefore critical. Among alternative resources, treated wastewater emerges as a promising and sustainable option. Its nutrient-rich composition not only reduces dependence on chemical fertilizers but also ensures a reliable year-round water supply while preventing environmental pollution. In Punjab, particularly Patiala, where intensive agriculture is both a strength and a challenge, integrating wastewater reuse with conventional water sources offers a practical pathway to balance supply and demand. Strengthening low-cost treatment systems, coupled with conservation measures, can enhance agricultural resilience, support rural livelihoods, and contribute to achieving long-term food and water security in line with sustainable development goals. The study concludes that despite slight increases in rainfall and runoff by 2040, water demand will continue to outpace supply, leaving a significant deficit. Effective conservation, irrigation efficiency, and groundwater recharge are essential to ensure sustainable water security.

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Conflict of Interests

The authors declare that there is no conflict of interest related to this article.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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