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Economic Viability of Underground Pipeline Irrigation System Projects in Punjab: Evidences from Randomized Control Trials

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ABSTRACT

Present study aims to evaluate the economics of Underground Pipeline Irrigation System (UGPS) installations completed in recent years in two districts of Punjab. Benefit-Cost Analysis (BCA) of Underground Pipeline System (UGPS) projects implemented in Patiala and Sangrur districts of Punjab during 2020–21 were evaluated The evaluation employed Randomized Control Trial (RCT) technique to assess economic and agronomic impacts of UGPS schemes implemented at both community and individual farmer levels. Beneficiary and control groups were randomly selected from an eligible farming population. Data was collected through structured interviews using pre-tested questionnaires. The primary indicators for impact assessment were Wheat Equivalent Yield (WEY), Benefit-Cost Ratio (BCR), and Payback Period (PBP), calculated based on Minimum Support Price of wheat and paddy. In Patiala, community-level UGPS projects showed improvements in WEY ranging from 8.91% to 20.32% over control farms, with BCR values between 1.28 and 1.38, and payback periods of 5 to 7 years. For individual farmer projects, WEY gains ranged from 3.5% to 25.6%, BCRs from 1.26 to 1.36, and PBP from 4 to 9 years. In Sangrur, community-level projects achieved WEY increases of 1.97% to 5.55%, BCRs from 1.27 to 1.32, and PBP from 4 to 10 years. Individual projects showed 3.45% to 17.24% higher WEY than controls, with BCRs between 1.27 and 1.34, and PBP ranging from 4 to 9 years. Overall, the study confirmed that UGPS significantly enhances crop productivity and offer favourable economic returns, making it a viable intervention for sustainable agricultural water management in Punjab.

1 | INTRODUCTION

Punjab has severely exploited its groundwater resources, raising major concerns for sustainability of its agriculture and food security (Roul *et al.*, 2021). Increasing dependence on groundwater has led to declining water tables, higher tube-well installation and operation costs, greater electricity usage, and deteriorating ground/irrigation water quality. Farmers have been tackling steep expenses for investment and maintenance of tube-wells*, i.e.* the cost of energy has escalated. An estimated ₹ 97.56 billion is needed to replace approximately one million centrifugal tube-wells with submersible pumps due to declining groundwater table. Groundwater depletion has also driven a sharp rise in energy demand, with agricultural electricity consumption increasing from 463.4 million kWh in 1970 to 10,248.6 million kWh in 2012 (ESO, 2013). Meanwhile, groundwater extraction efficiency declined from 5.19 m^3/kWh in 2004 to 3.85 m^3/kWh in 2009 (Singh, 2009). In-situ water harvesting techniques offers promise to address issue of water scarcity mitigation in this region (Bhat *et al.*, 2020).

At a global scale, growing water demand amid shrinking supplies is intensifying the search for alternative sources. In low-rainfall regions like Punjab (less than 1000 mm annually), paddy cultivation has raised serious concerns about water sustainability. Without intervention, groundwater depletion could reach 75% by 2050. Field unevenness further causes poor irrigation efficiency, leading to wastage of water, energy, and labour. Traditional water conveyance through earthen channels (*kuchha khals*) results in significant seepage and maintenance costs that particularly harm farm economics of tail-end users.

Punjab is a food bowl of India and has a prevalent wheat-rice cropping system. If the paddy–wheat rotation continues, the groundwater level in central Punjab is expected to decline sharply by 2023, it may fall below 70 feet in 66% of the area, below 100 feet in 34%, and below 130 feet in 7% (Sidhu *et al.*, 2010). Consequently, the sustainability of irrigated farming in the state faces a serious threat. To rejuvenate Punjab's agriculture, especially by identifying alternatives to the rice–wheat system and improving irrigation management, several expert committees and research groups have been working on possible solutions.

For combating these issues, government subsidy programs have promoted efficient water-saving/usage technologies, with reportedly mixed success. Subsidies aim to reduce groundwater extraction and stabilize water tables. In this regard, one of the technologies promoted by Punjab Department of Soil and Water Conservation is Under Ground Pipeline Systems (UGPS) through projects supported by NABARD, PIDB, MoA&FW, and others. The study aimed to achieve the following objectives i)To evaluate the economics of installed UGPS in two districts of Punjab ii) To compare the economics of installed UGPS with non-UGPS based agriculture. iii) To evaluate indirect benefits of UGPS.

HIGHLIGHTS

- The study evaluates the economic viability of underground pipeline irrigation systems (UGPS) in punjab using a Randomized Control Trial (RCT) and Benefit-Cost Analysis (BCA).
- UGPS adoption enhanced Wheat Equivalent Yield (WEY) by 1.97-25.6 %, with BCRs of 1.26-1.38 and payback periods of 4-10 years, confirming strong feasibility.
- The system reclaimed cultivable land, reduced water and energy losses, and replaced inefficient open channels.
- Findings, establish UGPS as a scalable, sustainable intervention for improving agricultural profitability and groundwater management.

2 | METHODOLOGY

Economic evaluation of underground pipeline systems (UGPS) implemented by Soil and Water Conservation Department, Government of Punjab under various central and state government funded schemes was undertaken under a consultancy project through Benefit-Cost Analysis (BCA) of samples selected following Randomized Control Trial (RCT) approach. Randomized control trial (RCT) is a way of doing impact evaluation in which the population receiving or has received the programme or policy intervention (beneficiary group) is chosen at random from the eligible population, and a control group that will not receive or has not received the intervention is also chosen at random from the same eligible population. The random assignment of members of the population eligible for treatment to either one or more treatment groups (who received the intervention treatment or variations of it) or to the control group (who received either no intervention or the usual intervention if the treatment is an innovation to an existing intervention) renders them comparable, and any difference between them is the effect of the treatment (Banerjee and Duflo, 2012). For the evaluation study, a selected eligible population at a location (sub-division of a chosen district) consisted of individual/group of farmers (as per subsidy scheme) that received the intervention (beneficiary group), namely the underground pipeline systems (UGPS), or did not receive the intervention (control group) due to certain administrative or local reasons, but can receive in the future when the constraints to implementing the interventions are removed.

2.1 | Sampling

For selection of the primary sampling units, i.e. beneficiary and control farmers, to be studied, multistage stratification was adopted. Though UGPS were implemented in many districts of Punjab state, only two districts were purposively chosen – Patiala and Sangrur – as they are among the most groundwater exploited districts of Punjab (Fig. 1) where groundwater level was reported to have fallen by more than 4.0 m during 2009-2019 (CGWB, 2021). In the first sub-strata, four tehsils of the chosen districts were purposively chosen –Nabha, Patiala, Patran and Rajpura –outof six (i.e. 66% sampling) in case of Patiala, and two (namely Sunam and Sangrur) out of seven (i.e. 28% sampling) in case of Sangrur – being among the highest groundwater exploited tehsils in their respective districts.For the next sub-strata, lists of implemented UGPS at different locations within the previous/higher substrata (i.e. in selected tehsils of the two districts) under two government funded schemes offering different percentages of subsidy depending upon the project being for individual farmer (50% subsidy) or group of farmers (90% subsidy) were procured from secondary sources. Out of the list of a tehsil, certain number of implemented UGPS projects were randomly selected as the second sub-strata. The percentage of sampling of implemented UGPS from the lists varied 11-30% and 20-33% in case of 50% and 90% subsidy schemes, respectively from Patiala district. In case of Sangrur district, the percentage was 20-21% and 20% in case of 50% and 90% subsidy schemes, respectively. In the last/third sub-strata, beneficiaries of installed UGPS with 50% subsidy were automatically selected being the sole beneficiary of 50% subsidized UGPS. In case of schemes giving 90% subsidy, which was for a group of more than ten benefitting farmers that were supplied irrigation water through a long distance UGPS from single node of a canal, three sampling units were randomly selected, one each from near, middle and farthest end of the UGPS for better representation of the beneficiary farmers. An equal number of respective controls were also selected from the control group of that location. The distribution of sampling units is given in Table 1. In total, 96 sampling units were utilized for the evaluation study.

2.2 | Data for benefit cost analysis

For undertaking benefit-cost analysis (BCA) of the UGPS installed under schemes offering different percentages of subsidy through the selected primary sampling units, their long-term data was required. Accordingly, provision was made for collection of the data through personal interviews of the randomly selected farmers of both beneficiary and control kind on a well-structured pre-tested questionnaire (Annexure-1). For pre-testing the questionnaire, a

TABLE 1 Sampling Units Distribution

District	Tehsil	Scheme Subsidy 90%		Scheme Subsidy 50%	
		Beneficiary	Control	Beneficiary	Control
Patiala	Nabha	3	3	3	3
	Patiala	3	3	3	3
	Patran	3	3	3	3
	Rajpura	3	3	3	3
Sangrur	Sunam	6	6	6	6
	Sangrur	6	6	6	6

Divisional office ofeach of the two selected districts tested it through personal interview of farmers. The questionnaire was then modified as per discussion with pre-testing Divisional offices. Total number of years of data collected for a UGPS project was as per data availability, depending upon the year of data collection after the UGPS started functioning. Secondary data such as information regarding schemes and the beneficiaries were obtained from Head office or Divisional offices of the Department.

As the evaluation was to be undertaken on RCT basis, the with/without project approach was utilized for the BCA. Therefore, the analysis took the difference in respective costs and benefits of the beneficiary farmers (i.e. with project) versus control farmers (i.e. without project) as the additional costs and benefits, respectively due to the UGPS intervention at a location in a scheme.

For each farmer's kind, data was collected of crop and livestock production activities, as these are the main sources of livelihood of the farmers of the study area. All physical outputs produced and purchased/hired inputs utilized for the crop and livestock production activities by the sampled farmers were included in the analysis. However, cost and benefits of intermediate outputs produced and consumed within the farming system like dry/green fodder from crops and manure from livestock were not considered in the BCA; nevertheless, any quantity of these purchased as an input from market were utilized for the analysis. Constant prices were utilized of all inputs and outputs for estimating the costs and benefits for the 96 sampled farmers. These costs and benefits were constantly discounted at 7%, the average of best interest rates available for more than 5 years long term deposits in banks of the country, during the period of analysis. Externality in the form of the area freed from old open channel system by laying down of UGPS and cultivated as irrigated area was included in the BCA. The productive life of a UGPS was taken to be 15 years for the BCA, as beyond 15 years what maintenance cost will be incurred is not known. Hence the period of analysis of BCA was 15 years.

In case of livestock component, owned livestock of the sampled farmers were first converted into standard livestock unit (SLU). As command area of each studied UGPS was uniformly extrapolated to a bigger size of 100 acre, the size of the livestock component was also expected to be larger. Therefore, the actual size of the livestock component of each beneficiary farmer was also extrapolated to a larger herd size in proportion to the 100 acre size of the UGPS Command Area, and that herd size was utilized for the respective control farmer. The extrapolated herd size varied across UGPS benefitting farmers as the actual herd size varied across these farmers. In two 50% subsidy cases, where a benefitting farmer did not own livestock, the respective control farmer was also assumed not to own livestock to maintain comparability. In case of 90% subsidized UGPS, wherein one out of three beneficiary (three such cases) or control (one such case) did not own livestock, the effect of zero livestock was nullified by utilizing average of the other two beneficiary / control farmers'. In case of four 50% subsidized UGPS, where the lone control farmer did not own livestock (while the beneficiary farmer owned livestock), and so its income from livestock component of farming was zero, for comparability, the BCR was estimated from only the crop component of both the control and corresponding beneficiary for comparability.

In addition to BCA, wheat equivalent yield (WEY) following Bhattacharyya *et al.* (2010) and Ghosh *et al.* (2012) were estimated to set apart overall impact of UGPS from its non-usage in terms of comparable yield data. The yield of paddy was converted into wheat equivalent yield (WEY). The converted paddy yield of a year was then added to the actual yield of wheat in that year. Therefore, WEY expresses total yield (productivity) for the paddy–wheat crop sequence. It is the yield of wheat plus yield of paddy expressed in terms of wheat yield.Wheat equivalent yield (WEY) was estimated using the following formula:

$$WEY_x = Y_x(P_x/P_w)$$

where, WEY_x is the wheat equivalent yield of crop x (paddy)in kg per acre, Y_x is the economic yield of crop *x* (paddy) in kg per acre, P_x is the price of crop *x* (paddy)in Rs per kg, and P_w is the price of wheat in Rs per kg.

2.3 | UGPS Projects

Department of Soil and Water Conservation, Punjab implemented the UGPS projects under a subsidy scheme that provided 90% subsidy (scheme subsidy 90:10) in the total sanctioned amount of the project for group or community of beneficiaries. A summary of the UGPS projects installed with 90% subsidy scheme in the selected two districts of Punjab that were surveyed and evaluated in this study is presented in Table 2.

Department of Soil and Water Conservation, Punjab also implemented UGPS projects under a subsidy scheme that provided 50% subsidy in the total sanctioned amount of the project for a single beneficiary i.e. individual farmer. A summary of the UGPS projects installed with 50% subsidy scheme in the selected two districts of Punjab that were surveyed and evaluated in this study is presented in Table 3 and Fig. 1.

TABLE 2 Brief data of studied UGPS projects funded for community based irrigation system (scheme subsidy 90:10)

District/Tehsil	Village	Area covered under scheme (ha)	Length of pipeline laid (km)
		District Patiala	
Patiala	Sanour	161	3.9
Nabha	Tarkheti Kalan	11.68	0.9
Rajpura	Rurka Ghanaur	31.72	2.6
Patran	Haryau Kalan	113.94	3.2
		District Sangrur	
Sunam	Ramgarh Jawanda	129.2	5.3
	Chhahar	134.4	3.9
Sangrur	Rupaheri	187.2	4.6
	Saaron	104	2.2

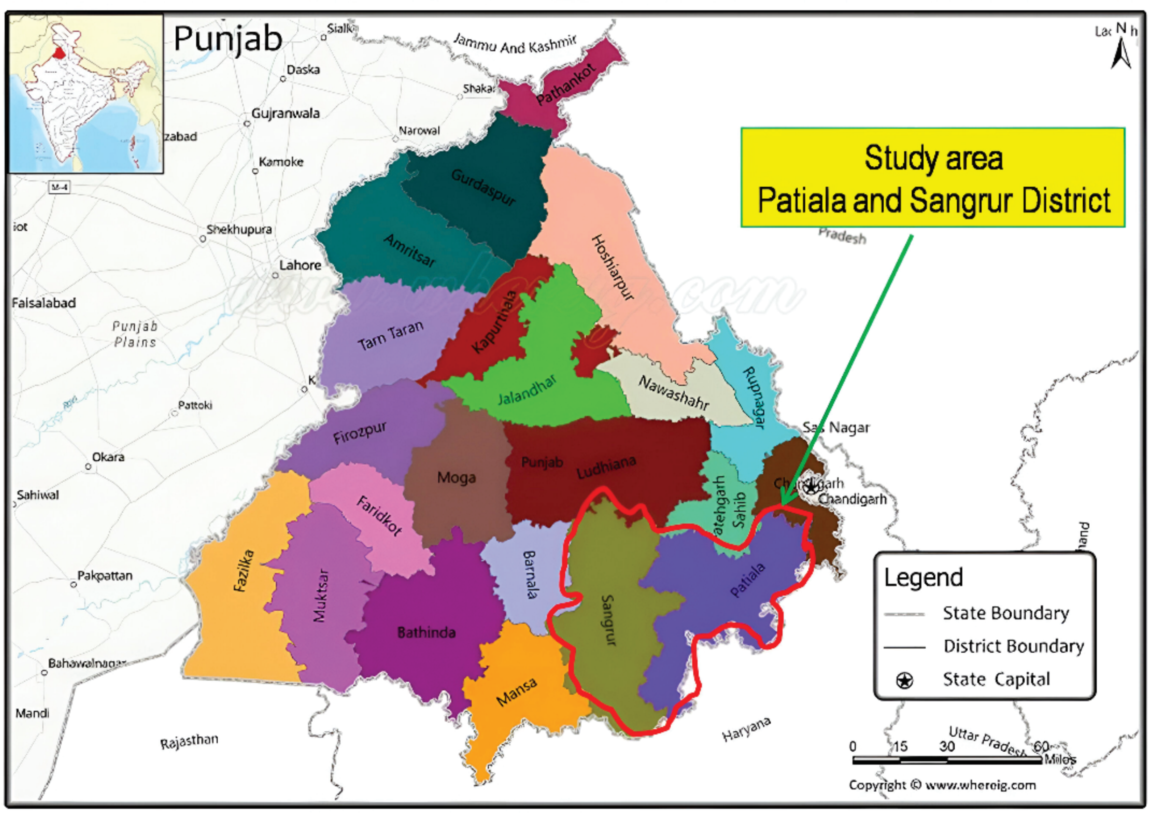

FIGURE 1 Selected Study area

TABLE 3 Brief data of location of studied UGPS projects for individual farmer based irrigation system (scheme subsidy 50:50)

District/Tehsil	Village	District/Tehsil	Village
Patiala		Sangrur	
Patiala	Kathmatti Chhamarkheri	Sunam	Sheron -1 Sheron -2
Nabha	Chana - Nathuwalia Chahal Khizarpur		Sheron -3 Sheron -4 Chhahar Biggarwal
Rajpura	Kheri-Mandalan Sehra Khutha-kheri	Sangrur	Fatehgarh Channa 1 Fatehgarh Channa 2 Fatehgarh Channa 3 Fatehgarh Channa 4 Banera
Patran	Duggal Kalan Shutrana Dodra		

3 | RESULTS AND DISCUSSION

3.1 | Wheat Equivalent Yield

3.1.1 | District Patiala (scheme subsidy 90:10)

The WEY for beneficiary farmers averaged 4535kg per acre, 9.72% higher than the control group's 4133 kg per acre (*Fig. 2.a*). In Tarkheri Kalan (Nabha), 972 m of UGPS covered 11.68 ha, benefiting six farmers with an average WEY of 5139 kg per acre, 16.27% above the control. Overall, beneficiaries achieved a 20.32% higher WEY. In Haryau Kalan (Patran), 3220 m of pipeline irrigated 113.94 ha for 33 farmers, yielding 5108 kg per acre, a 9.38% gain over the control (*Fig. 2a*).

3.2 | District Patiala (scheme subsidy 50:50)

Farmers in Punjab who installed UGPS under the 50:50 subsidy schemes showed notable yield improvements (*Fig. 2b*). In Nabha tehsil (Channa Nathuwalia, Chahal, Khizarpur), yields rose 8.1% to 19.1%; in Rajpura tehsil (Kheri Mandalan, Sehra, Kuthakheri), WEY was 5.34% to 16% higher; and in Patran tehsil (Shutrana, Dugal Kalan, Dodra), yields increased 4.10% to 24.25% compared to controls.

3.3 | Sangrur (Scheme subsidy 90:10)

In Ramgarh Jawanda, 5380 m of underground pipeline benefited 58 farmers, achieving a WEY of 4429 kg per acre, 5.55% higher than the control group. In Chhahar, 3985 m of UGPS served 48 farmers, with a WEY of 47.99 quntals per acre, 1.97% higher than control. In Rupaheri, UGPS covered 187.2 ha, benefiting 33 farmers and yielding 5367 kg per acre, a 4.84% increase. In Saaron, 2295 m of pipeline benefited 30 farmers, achieving 4853 kg per acre, 3.36% higher than control (*F ig. 3a*).

3.4 | Sangrur (Scheme subsidy 50:50)

In the Sangrur subdivision/tehsil, Banera and Fatehgarh Chhana villages were randomly selected, and beneficiary farmers from these villages were surveyed. The WEY among these farmers ranged from 5128 to 5667 kg per acre (*Fig. 2b*), which was higher than that of the respective control farmers, indicating the positive impact of the UGPS installation. The percentage increase in WEY attributed to the UGPS intervention ranged from 3.44% to 12.18%, as shown in *Fig. 3b*.

The adoption of UGPS made available additional cultivable area by replacing unlined 2 metre wide irrigation channels with narrow 1–1.5 foot bunds. In Patiala, 12696 m of pipeline were installed across 15 projects (four under 90:10 and eleven under 50:50 subsidy schemes), reclaiming 6348 m² of land. Similarly, in Sangrur, 20035 meters of UGPS were laid under 16 projects, making 10017 m² of land available for cultivation. Given a square acre, about 47.4 m² was saved per acre, enabling an additional 62 kg per acre of WEY, with the average WEY being 5261 kg per acre under the paddy-wheat system.

The findings of this study confirm that Underground Pipeline Systems (UGPS) are a technically and economically viable irrigation solution for Punjab,particularly in regions experiencing severe groundwater stress. The application of the Randomized Control Trial (RCT) technique provided credible empirical evidence, demonstrating significant improvements in crop yield and economic efficiency. In both Patiala and Sangrur districts, the WEY of UGPS beneficiaries consistently outperformed control groups, with yield increases ranging from 1.97% to 25.6%. These results are consistent with prior studies indicating that underground and pressurized pipeline systems reduce water loss that occurs in the form of seepage and evaporation from open irrigation channels being used for cultivation, thereby improving irrigation efficiency and crop response (Narayanamoorthy, 2005).

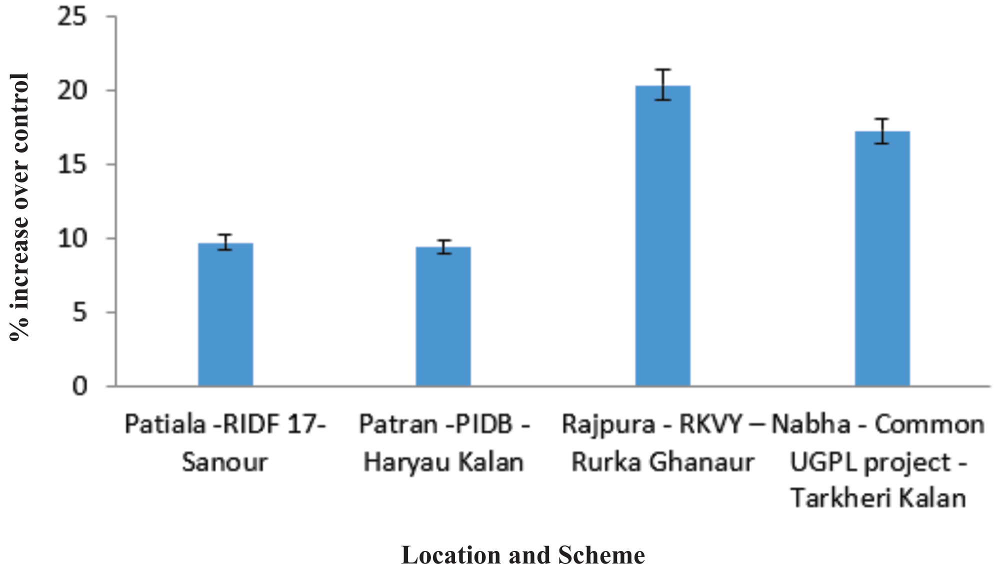

FIGURE 2a **Percent increase of WEY over control (Scheme subsidy 90:10) in district Patiala. Line on the bars are error bars (5 % level)**

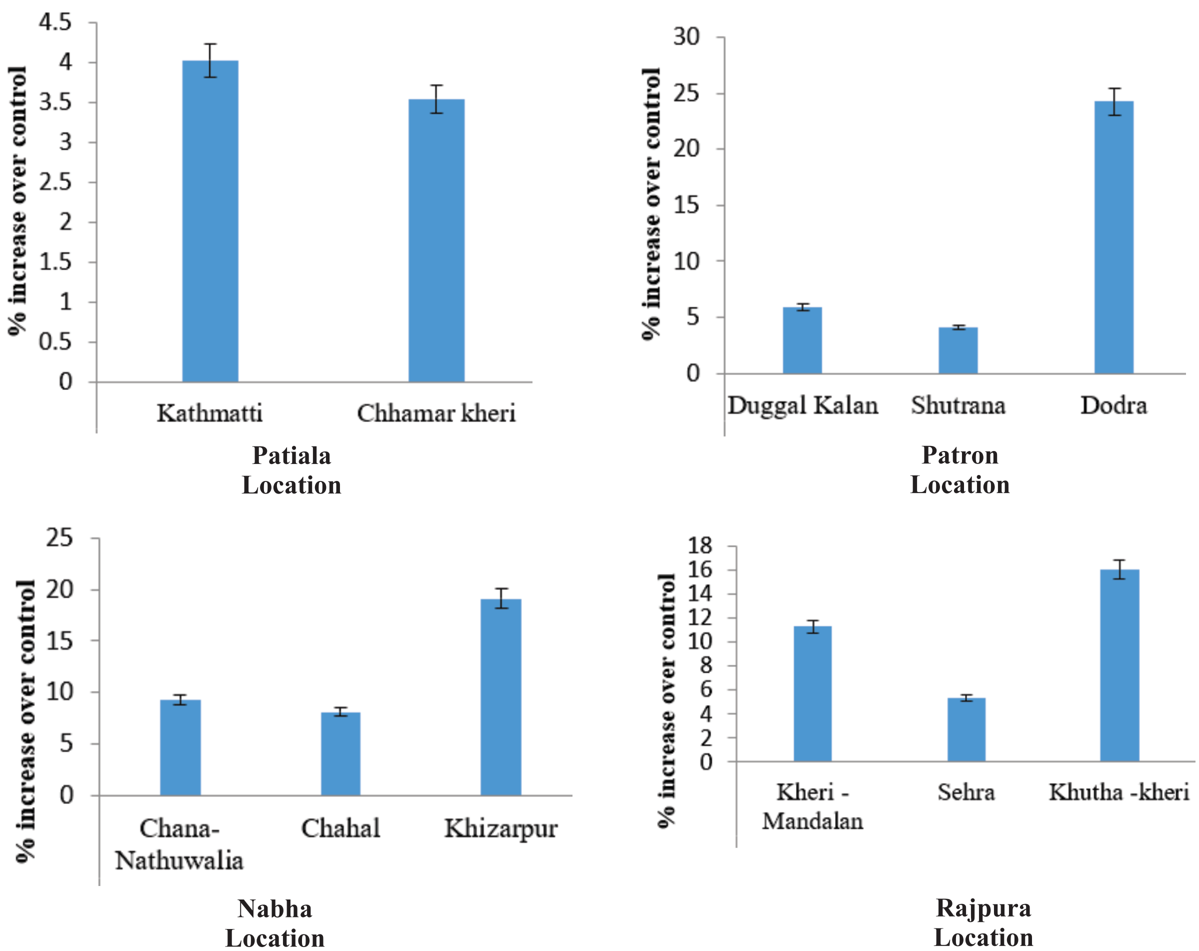

FIGURE 2b **Percent increase of WEY over control (scheme subsidy 50:50) in district Patiala. Line on the bars are error bars (5% level)**

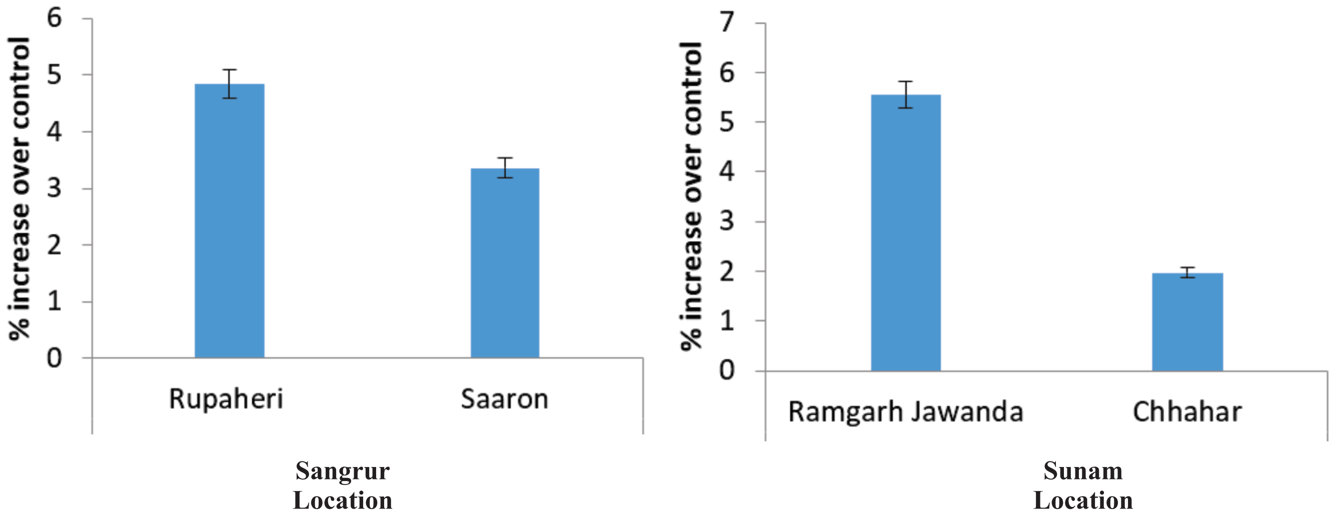

FIGURE 3a Percent increase of WEY over control (scheme subsidy 90:10) in district Sangrur. Line on the bars are error bars (5% level)

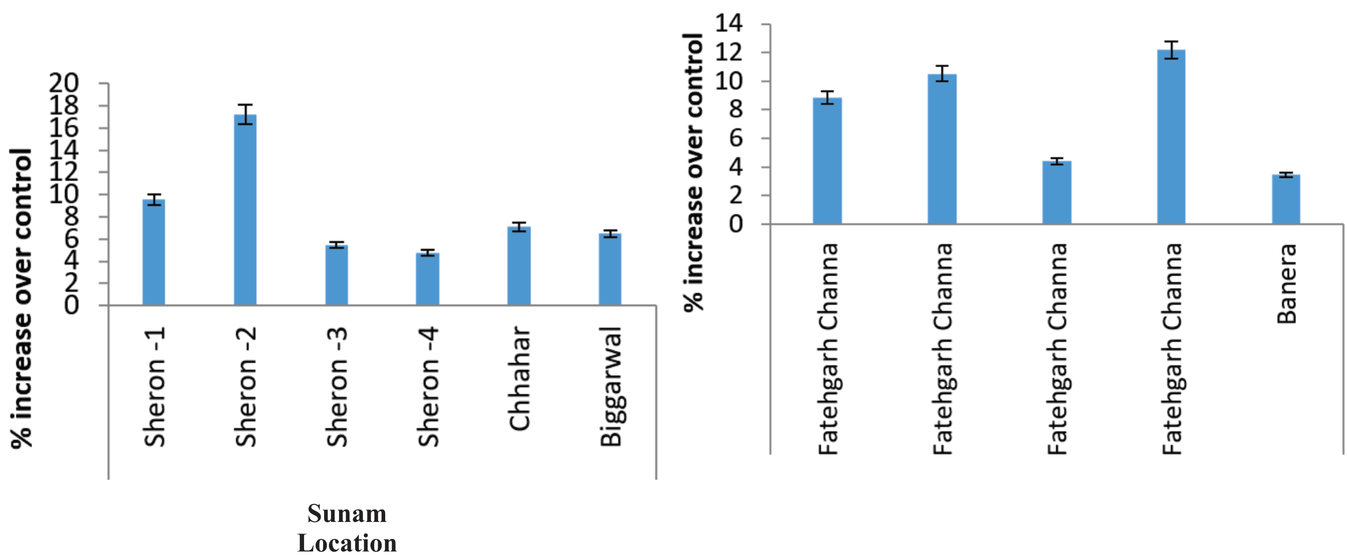

FIGURE 3b Percent increase of WEY over control (scheme subsidy 50:50) in district Sangrur. Line on the bars are error bars (5% level)

3.5 | Benefit-cost analysis

District Patiala (Scheme subsidy 90:10 and 50:50

Benefit-cost analysis, following the described methodology wherein the UGPS command area were standardized by extrapolating the results to a 100-acre landholding, was undertaken in terms of Benefit-Cost Ratio (BCR) and Payback Period (PBP). This allowed uniform assessment of economic viability across all surveyed beneficiary and control farmers of different landholding sizes. BCR ranged from 1.26 to 1.36 (Table 4), indicating a positive return on investment. The PBP was observed to range between 4 and 9 years, reflecting the time required to recover the initial investment through increased agricultural returns.

TABLE 4 Brief cost analysis of installing UGPS under different subsidy schemes for conveyance of canal water in district Patiala

Tehsil	Village	BCR	PBP (years)
	Scheme subsidy 90:10		
Patiala	Sanour	1.35	3
Nabha	Tarkheri Kalan	1.33	4
Rajpura	Rurka Ghanaur	1.30	7
Patran	Haryau Kalan	1.38	5
	Scheme subsidy 50:50		
Patiala	Kathmati	1.26	3
	Chhamarkheri	1.33	9
Patran	Duggal Kalan	1.32	8
	Shutrana	1.28	4
	Dodra	1.35	9
Rajpura	Kheri-Mandalan	1.34	6
	Khutha-kheri	1.31	5
	Sehra	1.26	8
Nabha	Chana-Nathuwalia	1.34	6
	Chahal	1.36	5
	Khizarpur	1.29	4

TABLE 5 Benefit cost analysis of installing UGPS for conveyance of canal water under different subsidy schemes for conveyance of canal water in district Patiala

Sub-division	Village	BCR	PBP (years)
	Scheme subsidy 90:10		
Sunam	Ramgarh Jawanda	1.32	9
	Chhahar	1.29	7
Sangrur	Rupaheri	1.30	5
	Saaron	1.27	4
	Scheme subsidy 50:50		
Sunam	Sheron -1	1.34	7
	Sheron -2	1.34	8
	Sheron -3	1.33	9
	Sheron -4	1.30	9
	Chhahar	1.33	4
	Biggarwal	1.27	8
Sangrur	Fatehgarh Channa -1	1.31	6
	Fatehgarh Channa -2	1.30	6
	Fatehgarh Channa -3	1.33	9
	Fatehgarh Channa -4	1.31	5
	Banera	1.31	7

3.6 | District Sangrur (scheme subsidy 90:10 and 50:50)

The economic analysis in Sunam region revealed that BCR ranged between 1.27 and 1.34, while the PBP varied from 4 to 9 years. In comparison, the Sangrur region recorded BCR values between 1.30 and 1.33, with the Payback Period ranging from 5 to 9 years. These findings are summarized in Table 5.

The observed BCR, ranging from 1.26 to 1.38 across different schemes, further validate the economic justification for UGPS investment. A BCR greater than 1.0 suggests that the benefits of the project outweigh its costs, even without considering long-term environmental externalities. These findings align with FAO (2020), which emphasizes the role of modern irrigation infrastructure in improving input-use efficiency and farm profitability. Furthermore, the variation in PBP (4–10 years) underscores the importance of tailoring subsidy levels and implementation models (community *vs* individual) to local conditions, as community-managed systems appeared to yield more consistent outcomes, echoing the results of Meinzen-Dick *et al.* (2002).

From a policy standpoint, these results support scaling up UGPS through targeted subsidies and farmer education programmes. However, complementary strategies—such as promoting crop diversification and efficient water-use practices—are essential for maximizing the long-term sustainability of such infrastructure. Continued evaluation is also critical to assess system durability, maintenance behavior, and broader environmental impacts over time.

4 | CONCLUSIONS

The implementation of Underground Pipeline Systems (UGPS) in Punjab's Patiala and Sangrur districts has yielded notable agronomic and economic gains. This study based on Randomized Control Trial (RCT) showed Wheat Equivalent Yield (WEY) improvements of 1.97% to 25.6% and Benefit-Cost Ratio (BCR) between 1.26 and 1.38, confirming economic viability with Payback Period (PBP) of 4 to 10 years. The study underscores the value of RCT based approach in assessing agricultural interventions. It suggests scaling UGPS to similar regions to improve water efficiency, farm income, and long-term resilience in water-scarce areas.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be provided on request.

AUTHOR'S CONTRIBUTION

PP designed and executed the study and prepared the manuscript. SP and PD contibuted to data collection and manuscript preparation. OP Premi, Manoj Kumar and OPS Khola assisted in data collection.

Supplementary data available in online version.

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