The Indian Journal of Agricultural Sciences **96** (8): 1056–1062, August 2026/Article
https://doi.org/10.56093/ijas.v96i8.177243

Economic evaluation of surface and subsurface drip fertigated basmati rice (*Oryza sativa*)–wheat (*Triticum aestivum*)–mungbean (*Vigna radiata*) cropping system

VED PRAKASH MEENA[1], KHAJANCHI LAL[1]*, CHANDRA PRAKASH MEENA[2], MANOJ KHANNA[1], P S BRAHMANAND[1], ARPULA SAIRAM[1], NIVETA JAIN[3], KAPILA SHEKHAWAT[3], MAHESH CHAND MEENA[3], SUSAMA SUDHISHRI[1], A S BRAR[4] and RAMESHI MEENA[5]

ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

Received: 19 March 2026; Accepted: 28 July 2026

ABSTRACT

Low water-use efficiency and increasing water scarcity necessitate efficient irrigation management to sustain the productivity of the predominant basmati rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.)–mungbean (*Vigna radiata* L.) cropping system in the Indo-Gangetic Plains. This field study was carried out to evaluate the productivity and economic feasibility of drip-fertigated basmati rice established by direct seeding (DSR) and transplanting (TPR), followed by wheat and mungbean under surface drip (SD) and subsurface drip (SSD) irrigation during 2020–21 and 2021–22 at ICAR-Indian Agricultural Research Institute, New Delhi. The treatments included three irrigation schedules [1.2, 1.4 and 1.6 crop evapotranspiration (ETc) for rice, with corresponding ETc levels of 0.6, 0.8 and 1.0 for wheat and mungbean], compared with a conventional control (flood irrigation with 100% recommended NPK fertilisers). However, transplanted rice was evaluated only under subsurface drip irrigation (SSD-TPR). It was observed that increasing the irrigation schedule from 1.2 to 1.4 ETc in rice and from 0.6 to 0.8 ETc in wheat and mungbean increased the yields of rice, wheat, mungbean and system rice equivalent yield (SREY) by 19.2, 36.6, 20.3 and 23.7%, respectively. System productivity under SSD-DSR, SSD-TPR and SD-DSR was 9.04, 8.96 and 8.55 Mg/ha, respectively and remained statistically comparable. At the 0.8/1.4 ETc schedule, fertigation with 100% NPK produced a significantly higher average SREY (9.49 t/ha) than the conventional practice (9.16 t/ha). Under SSD-DSR at 1.4 ETc in rice, SSD in wheat and mungbean at 0.8 ETc, and the overall system (0.8/1.4 ETc), net income was 12.1, 41.2, 57.0 and 27.5% higher, respectively, than under the conventional system. At the 0.8/1.4 ETc schedule, SSD-DSR recorded the highest BCR (2.03), followed by SSD-TPR (1.91), and SD-DSR at 1.0/1.6 ETc (1.89). Thus, adoption of this irrigation strategy may be a viable option for sustainable water management in the rice–wheat–mungbean cropping system.

Keywords: Crop evapotranspiration, Direct seeded rice, Economic feasibility, Rice equivalent yield, Transplanted rice

Agriculture is the largest consumer of freshwater resources globally, accounting for approximately 70% of global freshwater withdrawals and about 72% of total freshwater withdrawals worldwide (FAO 2024). In India, 56.4% of the net sown area was irrigated during 2022–23, of which only 23% was canal irrigated, while the remaining area depended primarily on tube wells and other groundwater sources (MoA&FW 2025). This trend indicates a growing reliance on groundwater to meet irrigation demand across different sectors of the economy (Singh *et al.* 2019, Jia *et al.* 2020). Such intensive groundwater extraction is largely driven by lenient water-use regulations and substantial electricity subsidies (CGWB 2019, Brar *et al.* 2022). The rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.)–mungbean (*Vigna radiata* L.) cropping system, widely practiced in north-western India, is among the largest consumers of irrigation water and relies heavily on groundwater resources (Aeschbach-Hertig and Gleeson 2012). During 2023–24, rice, wheat and mungbean occupied 47.8, 31.8 and 3.6 mha, producing 137.8, 113.3 and 5.3 mt of grain, respectively (MoA&FW 2025). The annual water requirement of this cropping system is estimated at 2,000–2,500 mm, contributing to rapid depletion of groundwater resources (Brar *et al.* 2022). Conventional puddled transplanted rice

[1]Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi; [2]Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan; [3]ICAR-Indian Agricultural Research Institute, New Delhi; [4]Punjab Agricultural University, Ludhiana, Punjab; [5]Govt. PG College (University of Kota, Kota, Rajasthan), Karauli, Rajasthan. *Corresponding author email: khajanchilal65@gmail.com

(PTR) requires continuous or prolonged flooding until shortly before harvest (Fageria *et al.* 2003). A substantial proportion of irrigation water is lost through evaporation, seepage and deep percolation beyond the root zone, leading to excessive groundwater withdrawal and declining aquifer levels (Hira *et al.* 2004). In contrast, direct seeded rice (DSR) reduces irrigation requirements and allows mechanised crop establishment. Earlier crop maturity under DSR also facilitates timely sowing of subsequent crops in the rotation.

Surface irrigation (SI) remains the most widely adopted irrigation method but results in significant water losses. Nearly 71% of applied irrigation water may be lost, and consequently water-use efficiency (WUE) rarely exceeds 45%. Such losses also contribute to nutrient leaching through deep percolation. These limitations highlight the need for efficient irrigation technologies such as drip fertigation, which can achieve WUE levels approaching 90% (Brar *et al.* 2019, Dhayal *et al.* 2023). Water-use efficiency can be further improved through subsurface drip irrigation (SSD), which delivers water directly to the root zone and minimises evaporation losses. Compared with surface drip irrigation (SD), SSD systems generally have a longer operational lifespan and are less affected by tillage operations.

Drip irrigation in field crops such as rice, wheat and mungbean may be economically feasible when appropriate irrigation methods and irrigation schedules are properly implemented. Till date, a comprehensive comparative economic evaluation of various drip irrigation methods and irrigation scheduling in puddled transplanted rice and DSR along with wheat and mungbean in a cropping system as a whole has not been undertaken. In light of this, the present study was designed to determine optimal irrigation and fertigation schedules for maximising crop yield and overall system productivity in the rice–wheat–mungbean sequence and evaluate the economic returns of using surface drip irrigation and subsurface drip irrigation systems in comparison with surface irrigation for finding the most effective management practices.

MATERIALS AND METHODS

The experiment was conducted during 2020–21 and 2021-22 at ICAR-Indian Agricultural Research Institute (28°38′23″N, 77°09′27″E, at an elevation of 228.6 m amsl), New Delhi. The total rainfall recorded during the first year and the second year was 1,031 mm and 1,706 mm, respectively.

Experimental layout: A field experiment on a rice–wheat–mungbean cropping system was conducted in a randomised complete block design with three replications. The treatments comprised three irrigation methods, viz. Sub-surface drip irrigation (SSD) in direct seeded rice (DSR)-wheat–summer mungbean; Surface drip irrigation (SD) in direct seeded rice (DSR)–wheat–summer mungbean; and Sub-surface drip irrigation (SSD) in transplanted rice (TP)–wheat–summer mungbean; with three irrigation schedules based on crop evapotranspiration (ETc) by using CROPWAT 8.0 software developed by FAO, viz. ETc 1.2 (rice)-ETc 0.6 (wheat)-ETc 0.6 (mungbean); ETc 1.4 (rice)-ETc 0.8 (wheat)-ETc 0.8 (mungbean); and ETc 1.6 (rice)-ETc 1.0 (wheat)-ETc 1.0 (mungbean). In addition, a conventional practice [surface irrigation with soil application of 100% recommended fertiliser doses (RDF)] was included for comparison. The gross plot size was 6 m × 2.8 m. The drip irrigation system comprised a 63 mm diameter PVC main line connected to two 50 mm sub-mains installed at a depth of 50 cm. Inline laterals of 16 mm diameter, fitted with laterals at 40 cm and emitters spaced at 30 cm and having a discharge rate of 2 L/h, were connected to the sub-mains. In the subsurface drip treatment, laterals were placed at a depth of 20 cm below the soil surface. Irrigation was scheduled twice a week for rice and two days interval for wheat and mungbean for drip irrigated treatments.

Rice variety ‘PB 1121’ was sown during the second fortnight of June for nursery raising and direct-seeded at 20 cm row spacing under the DSR treatment. In the SSD-TPR plots, all land preparation, including ploughing, puddling and field levelling, was completed before the installation of the subsurface drip laterals. The laterals were subsequently installed at a depth of 20 cm between crop rows using a trenching method, ensuring that no further deep tillage or puddling operations were carried out after installation. Light surface levelling was performed manually, wherever required, to avoid damage to the buried drip lines. Seedlings were transplanted during the second fortnight of July at a spacing of 20 cm × 15 cm under SSD-TPR and the conventional transplanted treatment. The crop was harvested during the first week of November. Wheat variety ‘HD 3086’ was sown in mid of November at 20 cm row spacing and harvested in first week of April. Mungbean variety ‘SML 832’ was sown in April at 30 cm row spacing and harvested in June.

The RDF (kg/ha) was 80:40:40 ($N:P_2O_5:K_2O$) for rice, 150:60:60 for wheat and 20:40:40 for mungbean. Nitrogen, phosphorus, and potassium were supplied through urea, mono-ammonium phosphate (MAP), and muriate of potash (MOP), respectively and were applied in three equal splits through fertigation at approximately 20-day intervals corresponding to the critical growth stages of each crop. In rice, fertigation was applied at transplanting/sowing [0 days after transplanting (DAT)/days after sowing (DAS)], 20 and 40 DAT/DAS, corresponding to crop establishment, active tillering and panicle initiation, flowering and grain filling stages. In wheat, fertigation was applied at sowing, 20 and 40 DAS, corresponding to sowing, crown root initiation (CRI) and tillering stages. In summer mungbean, fertigation was applied at sowing, 20 and 40 DAS, corresponding to establishment, branching and flowering-pod initiation stages. Under the conventional system, half of the nitrogen and the full doses of phosphorus and potassium were applied as basal through broadcasting at sowing, while the remaining nitrogen was top-dressed in two equal splits in rice, wheat and mungbean.

Yields: For evaluating system productivity, grain yields of wheat and mungbean were converted into rice equivalent

yield (REY) using market prices of ₹4,000, ₹2,125 and ₹8,558/100 kg grain for rice, wheat and mungbean, respectively. Straw prices were ₹100, ₹600 and ₹400/100 kg, respectively.

Economic analysis: Economic analysis considered an 80% subsidy on the micro-irrigation installation cost as per the Pradhan Mantri Krishi Sinchai Yojana guidelines; accordingly, only the remaining 20% of the installation cost was borne by the farmer and included in the analysis. The capital cost of the drip systems was annualised using the capital recovery factor (CRF) at an annual interest rate of 10%. An economic lifespan of eight years for the surface drip irrigation (SDI) system and 10 years for the subsurface drip irrigation (SSDI) system was assumed. The SSDI system included additional cost associated with trenching, installation and burial of laterals, which was incorporated into the initial investment before annualisation. The annualised fixed cost, together with operation and maintenance costs, was included in the economic analysis. The annual land rental value was assumed to be ₹1,00,000/ha and was apportioned as ₹37,500, 41,500 and 21,000/ha to rice, wheat and mungbean, respectively, based on their crop durations of 4.5, 5.0 and 2.5 months. The annual fixed cost (AFC) was calculated using CRF. Variable costs were calculated based on the actual expenses incurred for land preparation, seed, sowing/transplanting, fertilisers, irrigation, fertigation, plant protection chemicals, intercultural operations, harvesting, threshing, labour and operation and maintenance of the drip irrigation system. Electricity cost was calculated at ₹10/kWh.

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

Where I, Annual interest rate (10%); n, Economic life of the drip irrigation system (yr).

Net income was obtained by subtracting variable costs from gross income. The discounted benefit-cost ratio (BCR) was calculated as the ratio of the present worth of benefits to the present worth of costs (Michael 2007), assuming an opportunity cost (discount rate) of 7%. The present worth of benefits was estimated by discounting the annual gross returns from each crop over the economic life of the drip irrigation system, while the present worth of costs was obtained by discounting the annual production costs, including annualised capital, operation and maintenance and other cultivation costs, over the same period.

Statistical analysis: Data were analysed using analysis of variance (ANOVA) for a randomised complete block design (RCBD) (Gomez and Gomez 1984, Brar *et al.* 2022). A two-factor ANOVA was performed to evaluate the effects of irrigation method and irrigation schedule among the nine drip-irrigated treatments, whereas a one-factor ANOVA was used to compare all ten treatments, including the conventional system. Treatment means were compared at the 5% level of significance.

RESULTS AND DISCUSSION

Crop yields: Rice grain yield increased significantly when irrigation was scheduled at 1.4 or 1.6 ETc, producing 18–19% higher yield than 1.2 ETc. However, irrigation methods and their interaction with irrigation schedules did not significantly affect rice yield (Table 1). The highest grain yield (4.89 t/ha) was recorded under the conventional system, which was statistically comparable with yields obtained under SSD-DSR and SSD-TPR at 1.4 and 1.6 ETc. Averaged across irrigation schedules, yields under SSD-DSR and SSD-TPR were similar to the conventional system, whereas SD-DSR showed an 11.7% reduction. The lower grain yield under SD-DSR may be attributed to greater fluctuations in soil moisture and higher evaporative losses from the soil surface, which can reduce water availability during critical growth stages. In contrast, subsurface drip irrigation maintained a more uniform moisture distribution within the root zone, improving crop water uptake and thereby sustaining grain yields. Similar results have been reported in studies comparing DSR and PTR systems (Bhushan *et al.* 2007, Yadav *et al.* 2011).

Wheat yield was significantly influenced by irrigation schedules. Irrigation at 0.8 or 1.0 ETc produced 33.5–36.7% higher yields than 0.6 ETc and 8.3–10.9% higher than the conventional system, indicating that lower irrigation levels-imposed water stress. Grain yields under SD, SSD and surface irrigation were statistically similar. Mungbean yield was highest at 0.8 ETc, which was statistically similar to 1.0 ETc but significantly higher than 0.6 ETc. Grain yield under SSD irrigation was 5.8–7.0% higher than SD and surface irrigation, indicating improved root-zone moisture availability under subsurface drip systems. Higher yields at 0.8 and 1.0 ETc were attributed to adequate soil moisture during critical growth stages, which enhanced nutrient uptake and grain filling, whereas 0.6 ETc likely imposed moisture stress. The superior mungbean yield under SSD was associated with improved root-zone moisture distribution and reduced surface evaporation, resulting in better crop growth and yield.

System rice equivalent yield: System productivity, expressed as rice equivalent yield (REY), was highest under 0.8/1.4 ETc, which was 23.7% higher than 0.6/1.2 ETc and 3.5% higher than the conventional system (Table 1). Cropping sequences involving SSD-DSR and SSD-TPR produced REY comparable to the conventional system but higher than SD-DSR. The improved productivity under SSD can be attributed to efficient water and nutrient delivery directly to the root zone, reduced evaporation losses and improved soil moisture distribution (Sinha *et al.* 2017, Sairam *et al.* 2026). Adequate irrigation under 0.8/1.4 ETc likely enhanced physiological processes such as photosynthesis, nutrient uptake and cell elongation, resulting in improved crop growth and yield (Bathre *et al.* 2019, Patra *et al.* 2021, Dhayal *et al.* 2023).

Economic analysis: In rice, the total annual cost (Table 2) for DSR under drip irrigation (₹82,923–84,152/ha) was lower by ₹9,134–10,000 and ₹12,824–14,053 compared to the cost incurred in SSD-TPR and conventional method (₹96,976/ha), respectively. The lower annual cost under

Table 1 Rice, wheat, mungbean grain and system rice equivalent yield of R-W-M system (2020–2022)

Irrigation schedules	Methods of irrigation									
	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV
	Rice grain yield (t/ha)					Wheat grain yield (t/ha)				
0.6/1.2 ETc	4.05	3.88	4.03	3.99		3.81	3.54	3.85	3.73	
0.8/1.4 ETc	4.85	4.60	4.80	4.75		5.35	4.70	5.25	5.10	
1.0/1.6 ETc	4.78	4.65	4.74	4.72		5.05	4.95	4.95	4.98	
Mean	4.56	4.38	4.52		4.89	4.74	4.40	4.68		4.60
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	NS	0.19	NS	0.30		0.20	0.20	NS	0.35	
	Mungbean grain yield (t/ha)					System rice equivalent yield (t/ha)				
0.6/1.2 ETc	0.81	0.76	0.81	0.79		7.81	7.39	7.81	7.67	
0.8/1.4 ETc	0.98	0.89	0.97	0.95		9.80	8.99	9.66	9.49	
1.0/1.6 ETc	0.96	0.93	0.95	0.95		9.52	9.27	9.40	9.39	
Mean	0.92	0.86	0.91		0.86	9.04	8.55	8.96		9.16
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	0.04	0.04	NS	0.07		0.19	0.19	NS	0.31	

SSD, Sub-surface drip irrigation; SD, Surface drip irrigation; ETc, Crop evapotranspiration; DSR, Direct seeded rice; TPR, Transplanted rice; CONV, Conventional practice; MI, Methods of irrigation; IS, Irrigation schedule; SI, Surface irrigation; NS, Non-significant.

drip irrigation, despite the higher initial investment, was attributed to the annualisation of only the farmer's subsidised share (20%) of the installation cost over the system life and savings in irrigation, energy, labour and fertiliser application costs through drip fertigation. The highest net income was recorded under SSD-DSR with 1.4 ETc which was 12.1% followed by 1.6 ETc 8.9%; and SD-DSR with 1.6 ETc (3.2%) higher than TPC (Table 3). These treatments also achieved the highest discounted BCR (2.33), representing a 16% increase over TPC (2.01) (Table 4). This improvement was largely attributed to more favourable soil moisture conditions, which enhanced crop yields with only a marginal increase in irrigation costs incurred at higher irrigation schedule.

The total annual cost of cultivation for wheat under drip fertigation ranged from ₹84,018–85,770/ha, compared with ₹86,724/ha under the conventional practice. Net income and discounted BCR varied markedly across treatments. Net income and discounted BCR achieved by raising wheat irrigated through SSD at 0.8 ETc after the harvest of SSD-

Table 2 Total annual cost of rice, wheat, mungbean and R-W-M system pooled data (2020–2022)

Irrigation schedules	Methods of irrigation									
	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV
	Rice (₹/ha)					Wheat (₹/ha)				
0.6/1.2 ETc	82,923	83,789	92,923	86,545		84,018	84,980	84,018	84,339	
0.8/1.4 ETc	83,105	83,971	93,105	86,727		84,428	85,390	84,428	84,749	
1.0/1.6 ETc	83,287	84,152	93,287	86,909		84,808	85,770	84,808	85,129	
Mean	83,105	83,971	93,105		96,976	84,418	85,380	84,418		86,724
	Mungbean (₹/ha)					R-W-M system (₹/ha)				
0.6/1.2 ETc	54,399	54,880	54,399	54,559		2,21,341	2,23,649	2,31,341	2,25,444	
0.8/1.4 ETc	54,879	55,360	54,879	55,039		2,22,413	2,24,721	2,32,413	2,26,515	
1.0/1.6 ETc	55,029	55,510	55,029	55,189		2,23,124	2,25,433	2,33,124	2,27,227	
Mean	54,769	55,250	54,769		57,132	2,22,293	2,24,601	2,32,293		2,40,832

SSD, Sub-surface drip irrigation; SD, Surface drip irrigation; ETc, Crop evapotranspiration; DSR, Direct seeded rice; TPR, Transplanted rice; CONV, Conventional practice; R-W-M system, Rice–wheat–mungbean system.

DSR or SSD-TPR were similar but which was 35.6–41.2% and 15.6–18.2% higher than found in the conventional system. Averaged over irrigation scheduling, net income and BCR obtained from SSD irrigated wheat was 16.5 and 7.6% higher compared to SD irrigated wheat. The total annual cost of mungbean cultivation was comparable across treatments (₹54,399–55,510/ha) and similar to conventional method (₹57,132/ha). Net income ranged from ₹19,738–₹41,897/ha under drip systems. The highest net income was obtained with SSD-DSR with 0.8 ETc, which was 57% higher than conventional method (Table 3), along with the highest discounted BCR (1.70), reflecting a 20.2% increase over conventional method (1.42) (Table 4).

Across all three crops, irrigation scheduled at 1.4 ETc for rice under subsurface drip systems (SSD-DSR and SD-DSR) and 0.8 ETc for wheat and mungbean resulted in substantially higher net income and improved discounted BCR increased upto 57% and 20%, respectively compared to the conventional practice, indicating superior economic viability of the drip-based irrigation strategies

The net income (Table 3) and discounted BCR (Table 4) of the R-W-M cropping system varied across treatments involving different irrigation methods and schedules. However, drip fertigation systems can lower labour requirements by approximately 16–21%, enhance water-use efficiency and facilitate easier and more mechanised crop management (Dhayal *et al.* 2023, Sairam *et al.* 2025). Net income and BCR of R-W-M cropping system irrigated at 0.8/1.4 ETc was at par with 1.0/1.6 ETc but 1.64 and 1.25 folds higher than that at 0.6/1.2 ETc. It can be ascribed to optimal soil moisture regimes favouring higher crop yields with little extra cost on irrigation water at frequent irrigation schedule. Similar observations were reported by Brar *et al.* (2019) who found that drip-irrigated crops at 0.8/1.4 and 1.0/1.6 ETc achieved higher gross returns, net returns, and benefit-cost (B:C) ratios than those irrigated at 0.6/1.2 ETc. The highest net income (Table 3) was recorded under SSD-DSR with 0.8/1.4 ETc at ₹245,265/ha, representing a 27.5% increase over the conventional practice which yielded ₹192,359/ha. This treatment also achieved the highest discounted BCR (Table 4) of 2.03, which is 16.9% higher than conventional (1.74). Similarly, SSD-TPR with 0.8/1.4 ETc produced a net income of ₹228,228/ha (+18.6%) and a BCR of 1.91 (+10.2%) compared to conventional. Compared to SD, SSD irrigated R-W-M cropping system had better net income and BCR. In view of the better crop yields, differential installation cost and life span, annual cost of SSDI was considerably lower than SDI. Similar findings were recorded by Dhayal *et al.* (2023) in surface and sub-surface drip fertigated wheat–mungbean–maize cropping system. Treatments with irrigation scheduled at 1.0/1.6 ETc under both SSD-DSR (₹229,511; +19.3%) and SD-DSR (₹215,788; +12.2%) showed increase in net income relative to conventional. Their BCR values (1.96 and 1.89, respectively) were also higher than the conventional system. Overall, subsurface drip irrigation combined with an irrigation schedule of 1.4 ETc (rice) and 0.8 (wheat and mungbean) demonstrated the greatest economic advantage for the R-W-M cropping

Table 3 Net income from rice, wheat, mungbean and R-W-M system (pooled data 2020–2022)

Irrigation schedules	Methods of irrigation									
	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV
	Rice (₹/ha)					Wheat (₹/ha)				
0.6/1.2 ETc	84,410	76,418	73,593	78,140		38,418	29,232	40,183	35,944	
0.8/1.4 ETc	1,17,829	1,06,592	1,05,700	1,10,040		85,539	64,045	82,154	77,246	
1.0/1.6 ETc	1,14,439	1,08,491	1,02,781	1,08,570		75,844	71,497	72,459	73,267	
Mean	1,05,559	97,167	94,025		1,05,093	66,600	54,925	64,932		60,586
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	7,388	7,388	NS	12,042		4,742	4,742	8,213	8,218	
	Mungbean (₹/ha)					R-W-M system (₹/ha)				
0.6/1.2 ETc	25,063	19,738	25,325	23,375		1,47,891	1,25,388	1,39,101	1,37,460	
0.8/1.4 ETc	41,897	31,578	40,373	37,950		2,45,265	2,02,215	2,28,228	2,25,236	
1.0/1.6 ETc	39,228	35,799	37,912	37,646		2,29,511	2,15,788	2,13,152	2,19,484	
Mean	35,396	29,039	34,537		26,679	2,07,556	1,81,130	1,93,494		1,92,359
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	3,097	3,097	NS	5,730		7,742	7,742	13,409	12613	

SSD, Sub-surface drip irrigation; SD, Surface drip irrigation; ETc, Crop evapotranspiration; DSR, Direct seeded rice; TPR, Transplanted rice; CONV, Conventional practice; MI, Methods of irrigation; IS, Irrigation schedule; SI, Surface irrigation; R-W-M system, Rice–wheat–mungbean system; NS, Non-significant.

Table 4 Benefit-cost ratio (B:C ratio) of rice, wheat, mungbean and R-W-M system pooled data (2020–2022)

Irrigation Schedules	Methods of irrigation									
	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV	SSD-DSR	SD-DSR	SSD-TPR	Mean	CONV
	Rice					Wheat				
0.6/1.2 ETc	1.95	1.85	1.73	1.84		1.41	1.30	1.43	1.38	
0.8/1.4 ETc	2.33	2.19	2.06	2.19		1.94	1.69	1.90	1.85	
1.0/1.6 ETc	2.29	2.21	2.03	2.18		1.83	1.77	1.79	1.80	
Mean	2.19	2.08	1.94		2.01	1.73	1.59	1.71		1.64
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	0.08	0.08	NS	0.13		0.05	0.05	0.09	0.09	
	Mungbean					R-W-M system				
0.6/1.2 ETc	1.41	1.31	1.41	1.38		1.61	1.51	1.55	1.55	
0.8/1.4 ETc	1.70	1.52	1.67	1.63		2.03	1.83	1.91	1.93	
1.0/1.6 ETc	1.65	1.59	1.63	1.62		1.96	1.89	1.85	1.90	
Mean	1.59	1.47	1.57		1.42	1.87	1.74	1.77		1.74
LSD (p=0.05)	MI	IS	MI×IS	SI		MI	IS	MI×IS	SI	
	0.05	0.05	NS	0.10		0.03	0.03	0.06	0.05	

SSD, Sub-surface drip irrigation; SD, Surface drip irrigation; ETc, Crop evapotranspiration; DSR, Direct seeded rice; TPR, Transplanted rice; CONV, Conventional practice; MI, Methods of irrigation; IS, Irrigation schedule; SI, Surface irrigation; R-W-M system, Rice–wheat–mungbean system; NS, Non-significant.

system, with substantial improvements in both profitability and benefit-cost efficiency over conventional methods.

Compared to mechanised dry seeding of rice, transplanting of rice into puddled soil (PTR) is costlier as it is labour intensive and requires high irrigation water and fuel requirement for tillage and extraction for water from declining groundwater table (Kumar and Ladha 2011). Alam *et al.* (2018) also found 9% less cost of production in DSR in comparison with PTR, which led to a small increase in the gross margin and BCR of DSR.

The results demonstrated that irrigation methods and scheduling significantly influenced productivity and profitability of the rice–wheat–mungbean cropping system. Across crops, subsurface drip irrigation (SSD), particularly when combined with optimal irrigation scheduling, consistently outperformed the conventional surface irrigation system. Among irrigation schedules, 1.4 ETc for rice and 0.8 ETc for wheat and mungbean proved most effective in enhancing grain and straw yields. At the system level, irrigation scheduled at 0.8/1.4 ETc recorded the highest rice equivalent yield, indicating superior overall productivity of the cropping sequence. Economic analysis further substantiated the yield findings. Overall, subsurface drip irrigation scheduled at 0.8/1.4 ETc emerged as the most productive and economically viable option for the rice–wheat–mungbean cropping system under the experimental conditions. Adoption of this irrigation strategy may be able to enhance system productivity, resource-use efficiency and farm profitability while ensuring sustainable water management.

REFERENCES

Aeschbach-Hertig W and Gleeson T. 2012. Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience* **5**(12): 853–61. https://doi.org/10.1038/NGEO1617

Alam M J, Humphreys E, Sarkar M A R and Yadav S. 2018. Comparison of dry seeded and puddled transplanted rainy season rice on the High Ganges River Floodplain of Bangladesh. *European Journal of Agronomy* **96**: 120–30. https://doi.org/10.1016/j.eja.2018.03.006

Bathre S, Nema R K and Bhan M. 2019. Growth and yield influenced by wheat varieties on different dates and irrigation levels. *International Journal of Agricultural Science* **11**(10): 8446–51.

Bhushan L, Ladha J K, Gupta R K, Singh S, Tirol-Padre A, Saharawat Y S and Pathak H. 2007. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. *Agronomy Journal* **99**(5): 1288–96. https://doi.org/10.2134/agronj2006.0227

Brar A S, Buttar G S and Vashist K K. 2019. Enhancing crop and water productivity of spring maize (*Zea mays*) through drip fertigation. *Indian Journal of Agronomy* **64**(1): 87–92. https://doi.org/10.59797/ija.v64i1.5238

Brar A S, Kaur K, Sindhu V K, Tsolakis N and Srai J S. 2022. Sustainable water use through multiple cropping systems and precision irrigation. *Journal of Cleaner Production* **333**: 130117. https://doi.org/10.1016/j.jclepro.2021.130117

CGWB. 2019. Dynamic Groundwater Resources of India. Central Groundwater Board, Government of India, New Delhi.

Dhayal D, Lal K, Sindhu V K, Khanna M, Sudhishri S, Singh M and Chakraborty D. 2023. Productivity and profitability of drip fertigated wheat (*Triticum aestivum*)–mungbean (*Vigna*

radiata)–maize (*Zea mays*) cropping system. *The Indian Journal of Agricultural Sciences* **93**(3): 284–89. https://doi.org/10.56093/ijas.v93i3.133361

Fageria N K, Slaton N A and Baligar V C. 2003. Nutrient management for improving lowland rice productivity and sustainability. *Advances in Agronomy* **80**: 63–152. https://doi.org/10.1016/S0065-2113(03)80003-2

FAO. 2024. AQUASTAT Database. Food and Agriculture Organisation of the United Nations.

Gomez K A and Gomez A A. 1984. *Statistical Procedures for Agricultural Research*, 2nd edn. John Wiley and Sons, New York.

Hira G S, Jalota S K and Arora V K. 2004. Efficient management of water resources for sustainable cropping in Punjab. Research Bulletin No. 20. Department of Soils, Punjab Agricultural University, Ludhiana.

Jia X, Hou D, Wang L, O'Connor D and Luo J. 2020. The development of groundwater research in the past 40 years: A burgeoning trend in groundwater depletion and sustainable management. *Journal of Hydrology* **587**: 125006. https://doi.org/10.1016/j.jhydrol.2020.125006

Kumar V and Ladha J K. 2011. Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy* **111**: 297–413. https://doi.org/10.1016/B978-0-12-387689-8.00001-1

Michael A M. 2007. Economic evaluation of irrigation projects and water pricing policy. *(In) Irrigation: Theory and Practice*, pp. 695–724. Vikas Publishing House Pvt Ltd, Noida, Uttar Pradesh.

MoA&FW. 2025. *Annual Report 2024–25.* Department of Agriculture and Farmers Welfare, Krishi Bhawan, New Delhi.

Patra K, Parihar C M, Nayak H S, Rana B, Singh V K, Krishnan P, Pandey R, Mandal B N, Rathi N, Meena B R, Singh L K, Sidhu H S and Jat M L. 2021. Crop performance and nitrogen use-efficiency in maize under conservation agriculture coupled with sub-surface drip fertigation. *The Indian Journal of Agricultural Sciences* **91**(3): 474–79. https://doi.org/10.56093/ijas.v91i3.112544

Sairam A, Lal K, Sindhu V K, Khanna M, Sudishri S, Brahmanand P S, Shivay Y S, Parihar C M, Prasad S, Abraham G, Gaber A and Hossain A. 2025. Coupling sub-surface drip irrigation and integrated crop management in a maize–wheat rotation for increased food, water and energy security in north-west India. *Food and Energy Security* **14**: e70158. https://doi.org/10.1002/fes3.70158

Sairam A, Lal K, Sudishri S, Khanna M, Brahmanand P S, Shivay Y S, Abraham G and Meena V P. 2026. Economic analysis of surface and sub-surface drip fertigated maize (*Zea mays*)–wheat (*Triticum aestivum*) system under different nutrient management practices and irrigation schedules. *The Indian Journal of Agricultural Sciences* **96**(1): 33–39. https://doi.org/10.56093/ijas.v96i1.162505

Singh O, Kasana A, Singh K P and Sarangi A. 2019. Analysis of drivers of trends in groundwater levels under rice-wheat ecosystem in Haryana, India. *Natural Resources Research* **29**: 1101–26. https://doi.org/10.1007/s11053-019-09477-6

Sinha I, Buttar G S and Brar A S. 2017. Drip irrigation and fertigation improve economics, water and energy productivity of spring sunflower (*Helianthus annuus* L.) in Indian Punjab. *Agricultural Water Management* **185**: 58–64. https://doi.org/10.1016/j.agwat.2017.02.008

Yadav S, Gill G, Humphreys E, Kukal S S and Walia U S. 2011. Effect of water management on dry seeded and puddled transplanted rice: Part 1: Crop performance. *Field Crops Research* **120**(1): 112–22. https://doi.org/10.1016/j.fcr.2010.09.002