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Harnessing rain hose technology for water-saving sustainable irrigation and enhancing blackgram productivity in garden land

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Blackgram, a protein-rich pulse crop (24%), is crucial for combating food insecurity, particularly in malnourished and economically weak countries. Enhancing blackgram production requires improved, input-saving management practices. Given the challenges of climate change and population growth, efficient water management is vital for increasing pulse productivity and water use efficiency with minimal investment. This study aimed to identify cost-effective irrigation methods to optimise blackgram yields. Experiments were conducted at the National Pulses Research Centre in Vamban, Pudukkottai, and the Agricultural College and Research Institute in Kumulur, Tiruchirappalli, during the *kharif* season of 2021 and 2022. The study compared different treatments of irrigation methods, such as check basin, raised bed, drip, sprinkler and rain hose irrigation. Results showed that the rain hose system maintained the highest soil moisture (23.93% at 10 cm depth and 19.71% at 20 cm depth). Even though drip irrigation resulted in a higher seed yield (1363 kg ha^{-1}), the rain hose system proved to be more cost-effective, saving 27.09% in costs and achieving a 15.23% higher benefit–cost ratio. These findings suggest that the rain hose method, combined with current agronomic practices, is a viable low-cost technique for sustainable blackgram cultivation, optimising water use and maximising profits. This research provides valuable insights into water-saving irrigation methods for pulse crops.

Keywords Blackgram, Rain hose irrigation, Soil moisture, Yield, Water productivity, Water use efficiency

Blackgram (*Vigna mungo* L.), a protein-rich legume (24% protein content), is essential for addressing global food security, particularly in developing countries plagued by malnutrition and economic instability. As a staple crop, it plays a significant role in the diets of millions and contributes to sustainable agricultural practices by enriching soil fertility through nitrogen fixation. In India, blackgram is a pivotal pulse crop, occupying approximately 4.63 million hectares, yielding 2.78 million tons with productivity of 987 kg ha^{-1}[1].With its short growth cycle and self-pollinating nature, blackgram is a staple food crop in Indian agriculture. Tamil Nadu significantly contributes to blackgram cultivation, spanning 0.407 million hectares with a production of 0.26 million tonnes and a productivity of 660 kg ha^{-1}. However, the potential of blackgram cultivation depends greatly on the provision of adequate irrigation, as moisture stress significantly limits its production worldwide. This is one of the reasons for low productivity in Tamil Nadu[2].

Blackgram growth exhibits a direct correlation with soil moisture, emphasising the necessity of an adequate water supply. The crop's total annual evapotranspiration ranges from 350 to 450 mm, with daily rates peaking at 6 to 8 mm/day[3]. Unscientific irrigation methods and excessive water application reduce water use efficiency, making it imperative to address the issue of water scarcity, particularly in arid and semi-arid regions[4]. Optimal soil moisture levels are crucial for blackgram during its vegetative growth stage (20–30 days after sowing [DAS]),

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leading to the production of more flowers and pods and ultimately higher yields. Currently, only 40% of the blackgram area is irrigated, highlighting the urgent need for cost-effective and water-saving irrigation methods to conserve substantial quantities of water and reduce production costs.

In addition, the increasing pressures of climate change and a burgeoning global population demand innovative approaches to enhance blackgram productivity and resource use efficiency[3,4]. The United Nations' Sustainable Development Goals, specifically Goal 6, emphasise the need to enhance water-use efficiency and ensure sustainable water withdrawals, thereby reducing the number of people affected by water scarcity[5]. Approximately 80% of the world's irrigated lands rely on flood or surface irrigation methods, with an application efficiency of only 30–50%, while drip irrigation achieves significantly higher efficiency, ranging from 70 to 90%[4–7]. In the context of agricultural sustainability, water management is a critical factor. Traditional irrigation methods often lead to water wastage and inefficiencies, which are exacerbated under the current climate variability. Therefore, adopting water-saving technologies is imperative to ensure the optimal use of available resources, enhance crop yields and improve the overall resilience of agricultural systems.

In India, conventional drip irrigation (CDI) has made significant strides since its commercial adoption in the early '70 s, with the area under drip irrigation currently surpassing that of the USA[8]. Substantial government subsidies have further accelerated its adoption across various states. However, in Tamil Nadu, the adoption of micro-irrigation, particularly drip irrigation technology, remains relatively low at 0.15 million hectares[9]. One of the major obstacles to the widespread adoption of drip irrigation is access to low-cost or free public irrigation water and subsidised electricity. To encourage the adoption of this technology, the emphasis should shift towards improving productivity with reduced water and nutrient application, ultimately reducing labour costs and increasing profits[2,9,10].

Marginal farmers in developing countries often lack access to capital-intensive and expensive drip irrigation systems, which are typically designed for larger landholdings or for high-value horticultural crops. These systems are not suited for small-scale farmers with limited resources and smaller plots of land, which are common in India[11]. The development of the low-cost rain hose (LCRH) system addresses this gap, offering an affordable alternative for small landholders, who constitute 60% of the total farming population in India[2]. The LCRH method is a low-cost spray irrigation technology that uses thin-walled, flexible plastic hoses (40 mm) with closely spaced holes (approximately 5 cm apart) for uniform water distribution. This system is suitable for closely spaced crops such as onions, vegetables, leafy greens and groundnuts, offering spray width coverage of up to 5–6 m and operating at a pressure of 1 kg/cm^2, with a spraying height of 1.5–2.0 m. It presents a promising opportunity to enhance the livelihoods of marginal farmers by providing a cost-effective and efficient irrigation solution.

Despite its potential, the performance of the LCRH system relative to CDI systems remains understudied. Therefore, this research aims to identify cost-effective irrigation methods for blackgram cultivation during the *kharif* season. Additionally, it seeks to assess the influence of irrigation methods on grain production, water productivity, water use efficiency and overall economics at specific locations. This study is novel in its approach to harnessing LCRH technology for blackgram cultivation, addressing a critical gap in sustainable water management practices. By comparing this innovative method with established irrigation techniques, the research aims to provide actionable insights into the benefits of rain hose technology, particularly in enhancing crop yields and reducing input costs in blackgram. With this background, the study was conducted at the National Pulses Research Centre (NPRC) in Vamban, Pudukkottai, and the Agricultural Engineering College and Research Institute (AEC&RI) in Kumulur, Tiruchirappalli, Tamil Nadu, using the location-specific high-yielding blackgram variety VBN11.

Materials and methods

Experimental locations and climatic conditions

The experiment was conducted at two distinct locations: the NPRC in Vamban, Pudukkottai, and the AEC&RI in Kumulur, Tiruchirappalli, both affiliated with Tamil Nadu Agricultural University, India. The trials took place during the *kharif* seasons of 2021 and 2022. The first location was at the NPRC in Vamban, Pudukkottai, which is geographically located at 10° 36′ N latitude and 78° 90′ E longitude at an elevation of 93 m above Mean Sea Level (MSL). The second location was at the AEC&RI in Kumulur, Tiruchirappalli, which is geographically located at 10° 56′ N latitude and 78° 49′ E longitude at an elevation of 72 m above MSL. During the blackgram cropping period in NPRC, Vamban, the amount of rainfall received was 120 mm, of which 50% of the rainfall was effective with eight rainy days, and the mean pan evaporation was 5.23 mm per day. The mean maximum and minimum temperatures were 36.97 °C and 25.59 °C, respectively. The mean relative humidity (RH) recorded was 89% at 07:22 h and 59.39% at 14:22 h. Climatic parameters prevailed at AEC&RI; the amount of rainfall received was 98 mm, of which 50% was effective with six rainy days, and the mean pan evaporation was 6.12 mm per day. The mean maximum and minimum temperatures were 35.73 °C and 24.48 °C, respectively. The mean maximum RH recorded was 88.46% and minimum RH was 57.24%. Weather parameters recorded during the study period are depicted in Fig. 1.

Soil characteristics

The soil at NPRC, Vamban, exhibited a sandy loam texture, while the soil at AEC&RI, Kumulur, possessed a sandy clay loam texture. Composite soil samples were collected from the respective research fields before the commencement of the experiment using a field auger. These soil samples were then separated employing the quadrant method, and various physiochemical properties of the soil were analysed as per the standard procedures (Table 1).

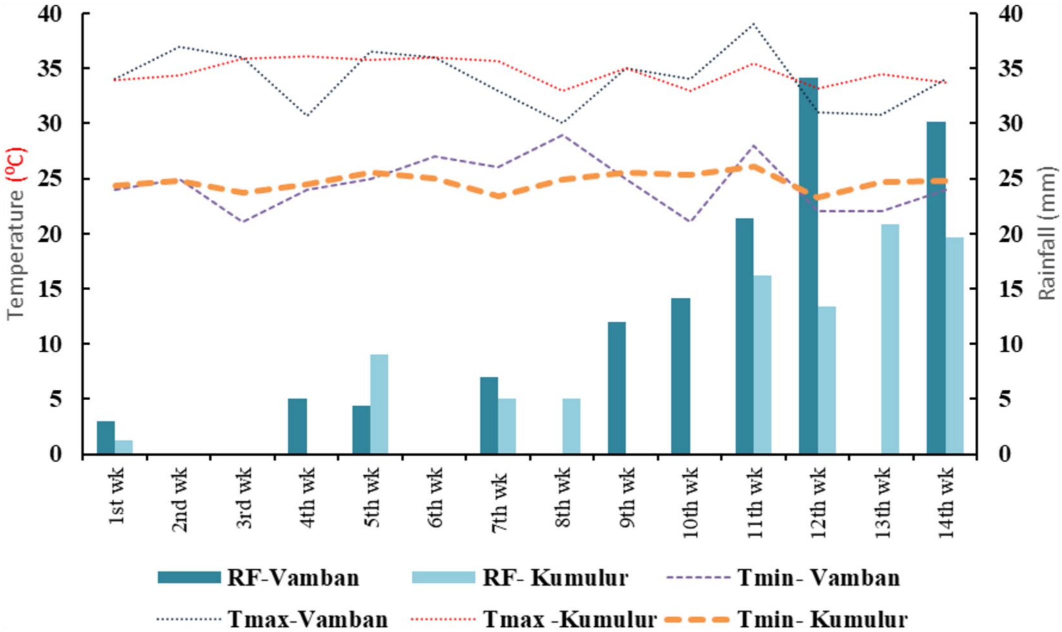

Figure 1. Meteorological parameters observed during the experimental period for both sites.

S.No.	Soil properties	NPRC, Vamban	IOA, Kumulur
1	Soil type	Sandy loam	Sandy clay loam
2	pH	6.09	7.70
3	Organic carbon (%)	0.32	0.54
4	Available nitrogen (kg ha^{-1})	162	215
5	Available phosphorus (kg ha^{-1})	39	14
6	Available potassium (kg ha^{-1})	133	195

Table 1. Initial soil properties of the experimental site.

Experimental design and field locations

Field experiments were carried out at the aforementioned research centres during the *kharif* seasons of 2021 and 2022. The experiments were conducted using the recommended practices for Blackgram cultivation, focusing on the VBN11 variety, which has a duration of 70–75 days. Blackgram VBN 11 was used for this study in both locations. The seeds were procured from the NPRC, Vamban, Pudukkottai, Tamil Nadu, India. The characteristic features of the VBN11 are provided in Table 2. The main objective of the study was to ascertain cost-effective irrigation methods for optimising Blackgram yields.

Treatment details

The experiment encompassed five distinct treatments, as outlined below, and the sketches of T_1 and T_2 are depicted in Fig. 2.

T_1—Check Basin Method: Employing traditional check basin irrigation. Check basins were formed with the dimensions of 3 × 2 m.

T_2—Raised Bed Method: Using raised beds for irrigation management. Raised beds were formed to a height of 15 cm, a bed width of 1.20 m and a length of 40 m with a tractor-drawn ridger.

T_3—Drip Irrigation System: Beds were designed for drip irrigation with a size of 60 cm, a height of 15 cm and 30 cm spacing between beds. Inline laterals were placed at the centre of the raised beds at a spacing of 90 cm with four Litres Per Hour (LPH) emitters spaced 40 cm apart.

T_4—Sprinkler Irrigation System: Flat beds were used for sprinkler irrigation. Sprinkler irrigation is a method of applying irrigation water similar to natural rainfall. Water is conveyed under the desired pressure (2.5 kg/cm^2) developed by a pump through a network of pipes, called mainlines and submains, to one or more laterals and is sprayed into the air through sprinkler nozzles so that it breaks up into small water drops (0.5–4 mm in size), which fall over the land or crop surface in a uniform pattern at a rate of 30 LPH, less than the infiltrability of the soil.

T_5—Rain Hose Irrigation System: Application of the rain hose irrigation system shown in Fig. 3.

Particulars	Description
Crop	Blackgram
Variety	VBN 11
Parentage	PU31 × CO 6
Year of release	2018
Season	Chithiraipattam (summer irrigated) Adipattam (*kharif*) Puratasipattam (*rabi*) Markazhi–Thaipattam (winter irrigated)
Duration (days)	70–75 days
Seed rate	20 kg ha^{-1}
Average yield (kg ha^{-1})	Rainfed condition: 865 kg ha^{-1} Irrigated condition: 940 kg ha^{-1}
100 seed weight (g)	4.5–5.0
Special features	Non scattering type Resistant to Mungbean Yellow Mosaic Virus disease

Table 2. Characteristic features of crop and variety used.

The Rain Hose, a flexible hose designed with nano punching technology, features a pattern of drip holes ensuring consistent water flow. With specifications including a wall thickness of 350 microns, a diameter of 40 mm and a continuous pattern of holes spaced approximately 5 cm apart, it discharges water at a rate of 200 LPH/metre under an operating pressure of 1 kg/cm^2. Its spray width spans 3 m, reaching a height of 1.5 m. Each roll spans 100 m, with 20 rolls (2000 m) covering a hectare, and it has an expected lifespan of five years.

Soil preparation and fertilisation
Before the commencement of the experiment, farmyard manure was uniformly spread at a rate of 12.5 tonnes per hectare and thoroughly incorporated into the soil during the last ploughing. The experimental field was ploughed once with a disc plough followed by cultivator ploughing twice. Finally, to break the clods and ensure optimum tilth for easy sowing and better crop emergence, a rotavator operation was used at NPRC, Vamban, and AEC&RI, Kumulur. Each irrigation method was allocated an area of 0.04 hectares for experimentation with different land configurations as mentioned above. These treatments were arranged in a Factorial Randomised Block Design (RBD) with four replications.

Fertilisation and fertigation through drip irrigation
As a standard practice, a uniform application of 25:50:25 NPK (Nitrogen, Phosphorus, Potassium) in kilograms per hectare was administered across all irrigation methods. It is worth noting, however, that under the drip irrigation system, fertigation was employed, applying fertilisers once in three days in adherence to specified quantities and timing. The details about the fertigation schedule are presented in Table 3. The fertigation sources for supplying NPK through drip irrigation were Urea, Mono Ammonium Phosphate, Sulphate of Potash and Mono Potassium Phosphate and 19:19:19% of NPK. Fertilisers for other irrigation systems were applied at the basal level using urea, super phosphate and potash.

Time of application through drip irrigation

Vegetative stage (1–20 DAS): 60:80:20 quantity % of NPK
Flowering stage (21–40 DAS): 40:10:40 quantity % of NPK
Pod formation stage (41–55 DAS): 0:10:40 quantity % of NPK
Maturity stage (55DAS to harvest): No fertigation

A drip tap was provided at the beginning of each lateral for controlled fertigation. For each lateral, a 4 mm diameter micro tube was fixed on either side of the drip tap, and the end of the micro tubes was attached to a plastic can with a 5-L capacity. During fertigation, the fertiliser solution was controlled by the tap. According to the treatment schedule, the required quantity of fertiliser solution was given to each fertigation through the plastic can, and then the fertiliser solution was injected through the surface drip system by adjusting the drip tap.

Sowing and agronomic practices
Blackgram seeds were treated with *Rhizobium* and *Phosphobacteria*, each at the rate of 30 g per kilogram of seed. These treated seeds were sown in lines with a spacing of 30 × 10 cm to accommodate four rows per bed. The recommended seed rate of 20 kg ha^{-1} was used. Sowing was carried out during the second week of July, and harvesting was completed during the last week of September in both experimental years. Pendimethalin herbicide was applied at a rate of 1.0 L a.i ha^{-1} on the third DAS. Gap filling was done at seven DAS for complete emergence wherever necessary, and thinning was carried out at 12 DAS to achieve the optimum plant population, maintaining one healthy plant per hill.

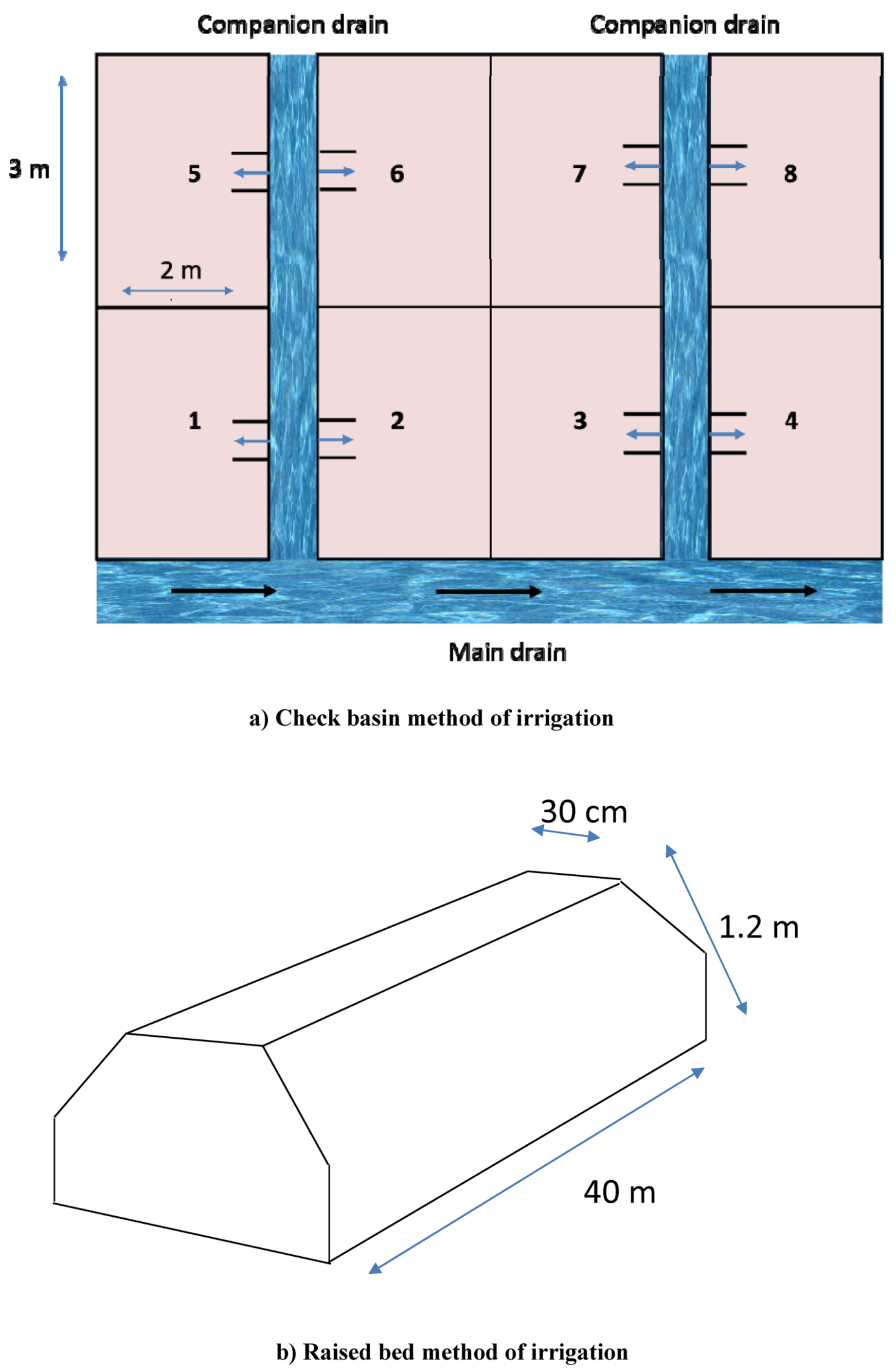

Figure 2. (**a**) Check basin method of irrigation. (**b**) Raised bed method of irrigation.

Figure 3. Field photos of blackgram crop under rain hose irrigation.

Cropstage (DAS)	Duration in days	No. of fertigation	Fertiliser grade	Total Fertiliser(kg ha^{-1})	Nutrient applied (kg ha^{-1}) N	P	K
0–20	20	6	MAP(12:61:0)Urea(46%N) SOP(50%K)	66.00 15.36 10.00	7.92 7.06 –	40.26 – –	– – 5.00
					14.98	40.26	5.00
21–40	20	6	19:19:19 Urea(46%N)SOP(50%K)	26.00 11.00 10.00	4.94 5.06 –	4.94 – –	4.94 – 5.00
					10.00	4.94	9.94
41–55	15	5	0:52:34(MKP)SOP(50%K)	9.66 14.24	– –	5.02 –	3.28 7.12
					–	5.02	10.40
			Total		24.98	50.22	25.34

Table 3. Fertigation details. *DAS* days after sowing, *MAP* mono ammonium phosphate, *MKP* mono potassium phosphate, *SOP* sulphate of potash, *N* nitrogen, *K* potassium.

Irrigation

Irrigation was provided through a drip system, with the first irrigation administered immediately after sowing. Subsequent irrigations were scheduled once in three days, guided by 100% daily pan evapotranspiration (PET). In the rain hose method of irrigation, the system was implemented in flat bed configurations, while check basin irrigation was used in check basin land configurations. Irrigation frequency was adjusted to once in seven days, calculated based on 100% PET using weather data from each centre.

Foliar application

Foliar application of 2% Diammonium phosphate (DAP) was conducted on 30 and 45 DAS. The DAP spray solution was prepared by soaking 10 kg of DAP in 25 L of water for 12 h to achieve a 2% concentration. The next morning, the supernatant solution was collected and diluted with 475 L of water. This diluted spray solution was then used for spraying at 30 DAS. The same procedure was repeated to prepare the 2% DAP solution for spraying at 45 DAS, using an Aspee backpack sprayer.

Plant protection

Initially, yellow sticky traps were installed in the blackgram field to control sucking pests. During the cropping period, leaf crinkle disease was observed in the blackgram field. Immediate measures were taken to control the spread of leaf crinkle disease by removing infected plants from the field. Under the guidance of an entomologist, suitable plant protection measures were implemented whenever the pest incidence level reached the economic threshold. These measures included protection against insects such as aphids, whiteflies, borers and caterpillars, achieved through the application of insecticides such as Dimethoate 30% Emulsified concentration at a rate of 2 mL per litre and Emamectin benzoate at a rate of 0.5 mL per litre.

Harvesting and threshing

The border rows were harvested first, followed by the net plot rows, and the yield was recorded. Harvesting involved picking the pods from the plants, and the seeds were manually separated by threshing, followed by winnowing. The separated seeds were then exposed to the sun for drying and weighed on a digital balance separately at 12% moisture content. Finally, the haulms were cut at ground level, dried in the field itself and weighed plot-wise.

Data collection

In each treatment, 10 plants were randomly selected and tagged with waxy-coated labels to record growth and yield parameters. The following observations on growth parameters, namely plant height, number of branches per plant and pod length (cm), as well as yield parameters, including number of pods per plant, 100-grain weight and grain yield, were recorded at the maturity stage. Additionally, a soil moisture study was conducted by measuring soil moisture percentage (volumetric basis) at 5-day intervals (one day before irrigation) at depths of 10 and 20 cm. These measurements were taken weekly using a direct digital soil moisture meter in all irrigation systems during the reproductive phase.

These data were meticulously recorded and are presented in tables. The initial and post-harvest soil samples were collected and analysed. For nutrient analysis, the following standard procedures were used for the determination of available nitrogen[12] and available phosphorus[13] and potassium content (kg ha^{-1}) using a Flame photometer[14].

Water requirement

The total water requirement (WR) for the cropping period was calculated by adding the total water applied and effective rainfall, expressed in millimetres (mm), using the following equation:

$$WR = Total\ Water\ Used\ (mm) + Effective\ Rainfall\ (mm)$$

Water use efficiency
Water use efficiency (WUE), measured in kg mm^{-1} ha^{-1}, represents the yield produced per unit of water used[15] and was calculated using the formula:

$$WUE = \frac{Economic\ yield\ of\ crop\ \left(kg\ ha^{-1}\right)}{Total\ Water\ Used\ (mm)}$$

Water productivity
Water productivity (WP), expressed in Indian rupees (INR) ha^{-1} mm^{-1}, considers both total water used and gross income produced[16] and was computed as follows:

$$Water\ productivity = \frac{Gross\ income\ \left(INR\ ha^{-1}\right)}{Total\ Water\ Used\ (mm)}$$

Economics
The total cost of cultivation of blackgram under all treatments was calculated by accounting for labour involved in various operations and materials used, including fertilisers, irrigation, harvesting and threshing. The economics of each treatment was evaluated by considering all aspects of crop production and prevailing market prices for inputs. In the case of irrigation methods, the cost involved in installation and field preparation were accounted for, and their lifetime and depreciation were also included in the cost economics. For instance, in the case of drip and sprinkler irrigation, the lifespan was considered as seven years, while for rain hose irrigation it was for a period of five years. Gross returns were calculated by multiplying the grain yield by the market rate.

Statistical analysis
The experimental data underwent statistical analysis in accordance with the methods[17]. Significance levels were assessed through AGRES Statistical software v 7.01, and critical differences were determined at the probability level of $p \le 0.05$ using Analysis of Variance for the RBD. Non-significant treatment differences were denoted as 'NS'.

Results
The collected data from the two years of study were pooled and analysed for various parameters using appropriate statistical methods.

Growth parameters
The growth parameters of blackgram, including plant height and the number of branches per plant, were assessed at the harvesting stage and are summarised in Table 4. The results of 2-year pooled mean indicated that among the various irrigation methods, drip fertigation yielded the significantly highest plant height at 49.98 cm and the highest number of branches per plant at 5.48. The rain hose method of irrigation system was performed next in order; however, it was found to be statistically equivalent, as indicated in the table with the same alphabetical letters (Table 4). In contrast, the check basin method of irrigation (T_1) recorded the lowest values for plant height and the number of branches per plant.

Treatments	Plant height at harvest (cm)			No. of branches per plant			No. of pods per plant		
	VBN	KUM	MEAN	VBN	KUM	MEAN	VBN	KUM	MEAN
T1	35.38	51.86	43.62^{c}	2.61	6.44	4.52^{d}	38.67	59.68	49.17^{e}
T2	37.84	51.48	44.66^{b}	3.37	6.77	5.07^{b}	42.56	70.92	56.74^{d}
T3	44.315	55.64	49.98^{a}	3.63	7.33	5.48^{a}	66.89	102.28	84.58^{a}
T4	39.67	51.06	45.36^{b}	2.7	6.80	4.75^{c}	52.05	85.05	68.55^{c}
T5	41.92	56.44	49.18^{a}	3.38	7.33	5.35^{a}	59.28	92.88	76.08^{b}
SEd	–	–	0.75	–	–	0.074	–	–	1.73
CD (P = 0.05)	–	–	1.63	–	–	0.16	–	–	4.61

Table 4. Effect of treatments on growth and yield parameters of blackgram (pooled mean of two years). Different alphabetical letters (a–e) indicate a significant difference between the treatments, while similar letters indicate that the treatments were on par.

Yield parameters

Yield parameters for blackgram, such as the number of pods per plant, the number of seeds per pod and 100-grain weight, were evaluated at the harvesting stage and are presented in Tables 4 and 5. The results showed that drip fertigation achieved the significantly highest pooled mean yield parameters, including the number of pods per plant (84.58), the number of seeds per pod (6.8) and test weight (4.89 g). These results translated to a higher seed yield of 1363 kg ha^{-1} and haulm yield of 3535 kg ha^{-1}. Rain hose irrigation also demonstrated favourable results with a seed yield of 1172 kg ha^{-1}.

Water use efficiency and water productivity

To assess crop productivity per unit of water used, water use efficiency and water productivity were analysed. A total of 280.3 mm of water (including rainfall received during the cropping period) was supplied through different irrigation systems to the blackgram crop. The results revealed that, despite the same quantity of water used in all methods, drip irrigation achieved the highest mean water use efficiency of 48.6 kg ha^{-1} mm and the highest water productivity of INR 292 ha^{-1} mm (Fig. 4) compared to other irrigation methods. The lowest water use efficiency and water productivity were observed in the check basin method of irrigation (T_1).

Soil moisture content

Soil moisture content was monitored by measuring soil moisture percentages using a digital soil moisture meter at 5-day intervals (one day before irrigation) during the reproductive phase. The changes in soil moisture content are presented in Fig. 5a,b. The results showed that the rain hose method of irrigation maintained significantly higher soil moisture content, with readings of 50.91% at a 10 cm depth and 35.47% at a 20 cm depth. Drip irrigation also maintained favourable soil moisture levels, with readings of 36.85% at 10 cm and 21.35% at a 20 cm depth. These conducive soil moisture conditions contributed to improved yield parameters. In contrast, the lowest soil moisture levels were observed in the check basin method of irrigation (T_1). Overall, rain hose irrigation recorded higher available soil moisture levels, with 23.93% and 19.71% at depths of 10 cm and 20 cm, respectively, compared to drip irrigation. Rain hose irrigation showed higher available soil moisture levels, with

Treatment	No. of seeds per pod			Test weight (g)			Seed yield (kg ha^{-1})			Haulm yield (kg ha^{-1})		
	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean
T_1	6.36	5.22	5.79^d	4.56	4.77	4.67	839	811	825^e	2768	2794	2781^d
T_2	6.51	5.45	5.98^c	4.66	4.83	4.74	981	946	964^d	2922	3046	2984^c
T_3	7.63	5.98	6.80^a	4.88	4.90	4.89	1404	1322	1363^a	3018	4053	3535^a
T_4	7.39	5.58	6.48^b	4.71	4.76	4.74	1081	1045	1063^c	2762	3509	3135^b
T_5	7.62	5.75	6.68^a	4.72	4.77	4.74	1201	1143	1172^b	2632	3781	3206^b
SEd	–	–	0.08	–	–	0.07	–	–	12.97	–	–	45.15
CD (P = 0.05)	–	–	0.177	–	–	NS	–	–	28.27	–	–	98.38

Table 5. Effect of treatments on yield parameters and yield of blackgram (pooled mean of two years). Different alphabetical letters (a–e) indicate a significant difference between the treatments, while similar letters indicate that the treatments were on par.

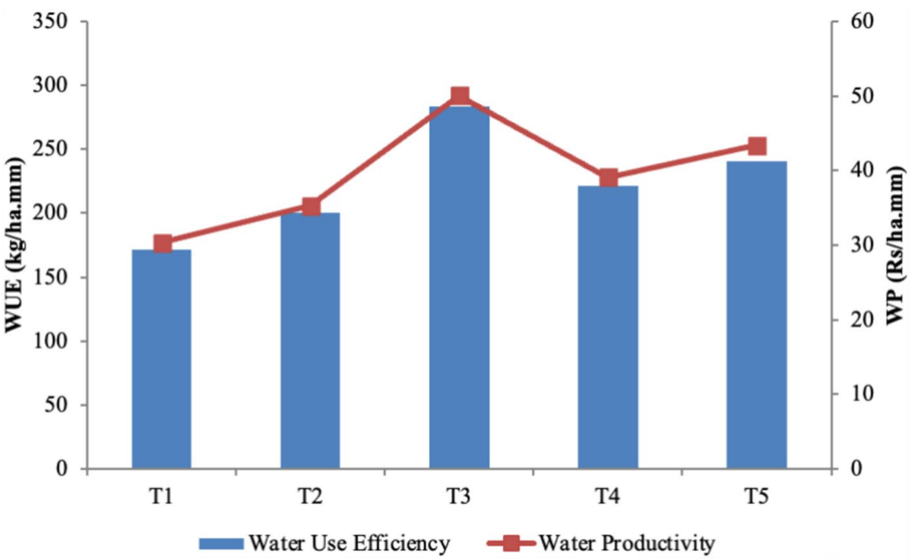

Figure 4. Water use efficiency (WUE) and water productivity (WP) for different methods of irrigation.

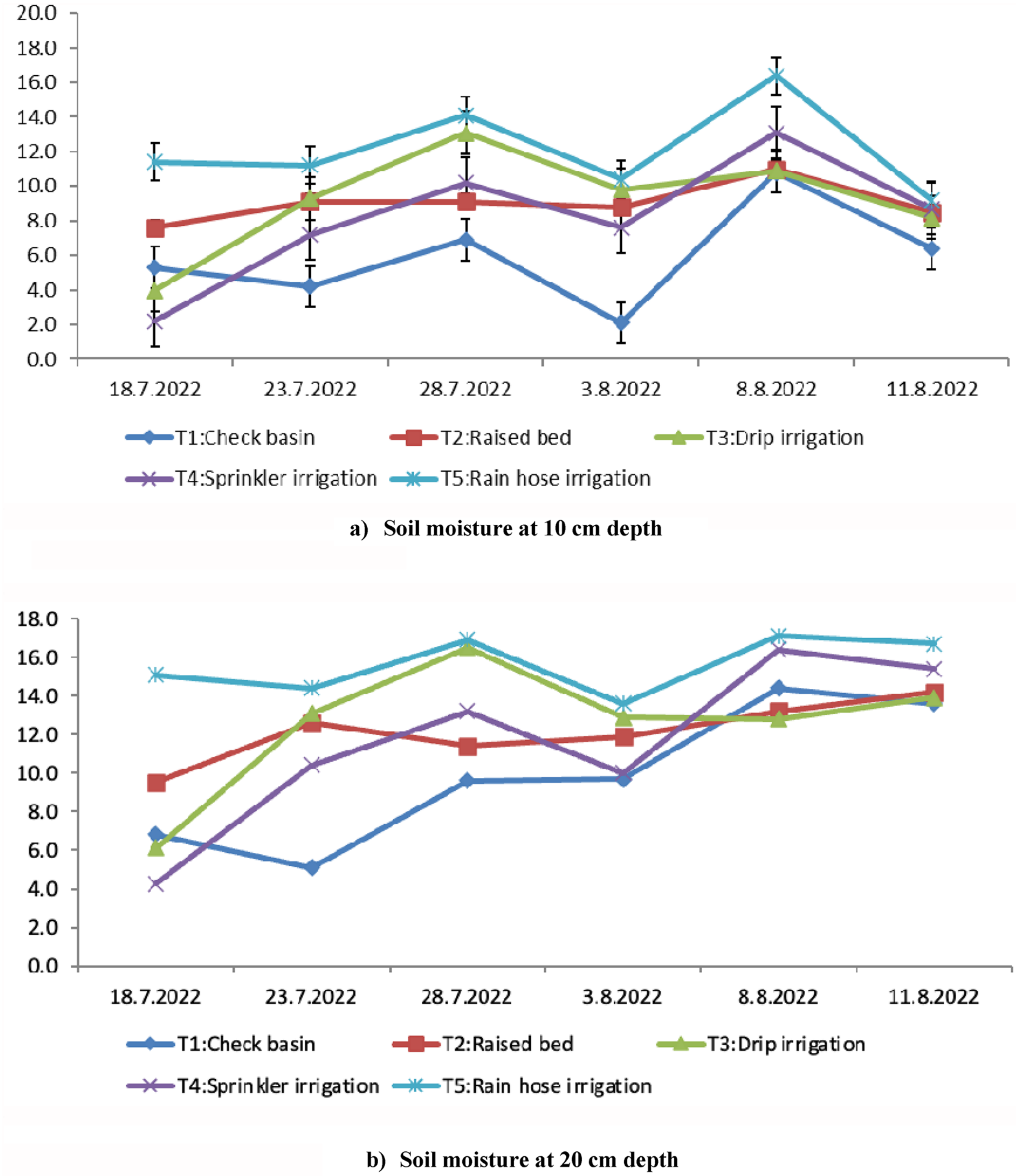

Figure 5. (**a**,**b**) Effect of treatment on change in soil moisture content (%) using digital soil moisture meter (pooled mean of 2 years).

measurements of 23.93% at a 10 cm depth and 19.71% at a 20 cm depth. This method likely distributes water more evenly across the soil surface, leading to better infiltration and retention of moisture at various soil depths. When compared to drip irrigation, rain hose irrigation consistently maintained higher soil moisture levels at both measured depths. Drip irrigation, while efficient in delivering water directly to the plant roots, may not provide as much moisture to the surrounding soil, resulting in lower overall soil moisture levels.

Economics

The total cost of cultivating blackgram per hectare using different irrigation methods ranged from ₹ 26,670 to 39,320 per hectare for this experiment. Drip irrigation incurred the highest cost at ₹ 39,320 per hectare (T_3), while the lowest cost of ₹ 26,670 per hectare was associated with the check basin method (T_1). Among the drip and rain hose irrigation methods, 27.09% cost savings were realised with the rain hose system compared to drip irrigation. The maximum mean gross income of ₹ 81,780 per hectare and net income of ₹ 44,460 per hectare were recorded under drip irrigation, followed by irrigation through the rain hose system, which achieved ₹70,890 per hectare of gross income and ₹ 43,220 per hectare of net income (T_5) (Table 6). However, rain hose irrigation resulted in a higher mean Benefit–Cost Ratio (BCR) of 2.48 compared to drip irrigation. This difference can be attributed to the increased cost associated with drip components and water-soluble fertiliser, which raised the production cost of the drip irrigation method.

Treatment	Cost of cultivation (Rs ha^{-1}) (with drip cost)			Cost of cultivation (Rs ha^{-1}) (without drip cost)			Gross return (Rs ha^{-1})			Net return (Rs ha^{-1}) (with drip)			Net return (Rs ha^{-1}) (without drip cost)			BCR (with drip cost)			BCR (without drip cost)		
	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean
T_1	26,867	26,473	26,670	26,867	26,473	26,670	50,340	48,630	49,485	23,474	21,907	22,690	23,474	21,907	22,690	1.90	1.815	1.86	1.90	1.82	1.86
T_2	28,866	27,473	28,169	28,866	27,473	28,169	58,860	56,760	57,810	29,995	29,287	29,641	29,995	29,287	29,641	2.06	2.08	2.07	2.07	2.09	2.08
T_3	40,018	38,623	39,320	36,018	34,623	35,320	84,240	79,320	81,780	46,223	42,697	44,460	48,223	44,697	46,460	2.13	2.065	2.10	2.35	2.29	2.32
T_4	29,365	27,973	28,669	27,365	25,973	26,669	65,370	62,670	64,020	36,466	35,697	36,081	37,466	36,697	37,081	2.22	2.24	2.23	2.36	2.43	2.39
T_5	29,368	27,973	28,670	27,368	25,973	26,670	72,030	69,750	70,890	43,663	42,777	43,220	44,663	43,777	44,220	2.46	2.495	2.48	2.66	2.69	2.67

Table 6. Effect of treatments on economics (pooled mean of two years).

Post-harvest soil available nutrients

Post-harvest soil analysis indicated that there was no decline in soil fertility due to the application of the recommended quantity of fertiliser based on blanket recommendations when compared with the initial soil fertility levels. The results of initial and post-harvest soil analyses revealed that the recommended quantities of NPK had sufficiently met the crop's requirements and did not diminish post-harvest soil fertility. The results were non-significant in the soil available organic carbon content and post-harvest soil available potassium in all the irrigation methods. Specifically, the pooled mean of the maximum available soil organic carbon 0.46% and soil available potassium was 171.5 kg ha^{-1} was registered in the drip irrigation method than other irrigation systems. Significantly higher nitrogen (196.0 kg ha^{-1}) and phosphorus (29.85 kg ha^{-1}) were recorded in blackgram cultivation under drip irrigation (T_3), followed by the rain hose method of irrigation (Table 7). In contrast, the lowest levels of available soil organic carbon, nitrogen, phosphorus and potassium were observed in the check basin method (T_1).

Discussion

The cultivation of pulse crops, such as blackgram, typically requires less irrigation water compared to cereal crops. Specifically, blackgram has been reported to need between 400 and 500 mm of water[18]. The primary objective of efficient irrigation practices is to maximise yields with minimal water input. Generally, pulse crops respond favourably to various irrigation methods, but micro-irrigation techniques, particularly drip irrigation, are especially effective for managing limited water resources[19]. During periods of acute moisture stress, providing one or two irrigations directly to the root zone of crops can significantly enhance crop growth and yield. Consequently, selecting the appropriate irrigation method is crucial for improving water use efficiency, conserving water and reducing costs. Water scarcity during the early stages of pulse crop growth can adversely affect germination, leading to reduced plant populations per unit area and ultimately impacting crop yields. Similarly, water shortages during flowering and pod formation stages can severely reduce the number of grains per pod, grain weight and overall yield[20]. This study attempted different irrigation methods with this hypothesis, and results showed statistically significant improvement in blackgram growth and yield.

Experimental results demonstrated significant improvements in the growth and yield parameters of blackgram, as well as overall yield, when drip and rain hose irrigation systems were employed compared to other irrigation methods. Several factors contributed to this enhancement, including the efficient and favourable movement of nutrients to the growing crops, reduced volatilisation and leaching losses of applied nutrients through drip fertigation compared to conventional fertiliser application methods. Micro-irrigation systems, such as drip and rain hose, maintain favourable soil–water–air proportions throughout the cropping period. The increased yield under the drip irrigation system can be mainly attributed to the uniform application of water-soluble fertiliser and the maintenance of soil moisture throughout the crop growth cycle. This, in turn, promotes better nutrient translocation from source to sink[2,21,22].

Rain hose irrigation demonstrated higher available soil moisture levels, measuring 23.93% at a depth of 10 cm and 19.71% at a depth of 20 cm. This method is likely more effective in distributing water evenly across the soil surface, leading to improved infiltration and retention of moisture at various soil depths. In comparison, drip irrigation, although efficient in delivering water directly to plant roots, may not distribute moisture as effectively to the surrounding soil, resulting in lower overall soil moisture levels.

Although drip irrigation resulted in higher yields and nutrient uptake, the rain hose system exhibited advantages in terms of available soil moisture and net profit. This can be attributed to the lower cost of rain hose irrigation compared to drip irrigation, along with its higher water discharge rate of 200 LPH, which sustains soil moisture over a longer period. Cultivating blackgram with the rain hose system, while following established agronomic practices, is crucial for realising a 27.1% cost reduction and a 15.32% higher BCR compared to drip irrigation. The nutrients applied are effectively dissolved and reach the root zone, creating favourable conditions for improved crop growth and blackgram yield.

Nitrogen, phosphorus and potassium are vital nutrients essential for the growth and development of blackgram. Nitrogen is crucial during the seedling stage, phosphorus supports active growth, seed development and energy storage, while potassium helps maintain water balance, stalk strength and nutrient transportation within the plant. Drip fertigation, which applies these nutrients directly to the root zone, enhances water and nutrient

Treatments	Organic carbon (%)			Available nitrogen (kg ha^{-1})			Available phosphorus (kg ha^{-1})			Available potassium (kg ha^{-1})		
	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean	VBN	KUM	Mean
T_1	0.315	0.575	0.445	165.5	220.3	192.9^{b}	38.1	15.3	26.68^{c,d}	136.5	196.5	166.5
T_2	0.315	0.575	0.445	165.5	218.5	192.0^{c}	37.8	15.6	26.70^{c,b}	138.0	199.8	168.9
T_3	0.330	0.59	0.460	169.5	222.5	196.0^{a}	42.9	16.9	29.85^{a}	141.0	202.0	171.5
T_4	0.315	0.575	0.445	166	219.0	192.5^{b}	39.1	15.1	27.10^{b}	137.0	198.0	167.5
T_5	0.320	0.58	0.450	167.5	220.0	193.8^{a}	41.7	16.2	28.90^{b}	139.5	200.5	170.0
SEd	–	–	0.006	–	–	1.53	–	–	0.42	–	–	2.19
CD (P = 0.05)	–	–	NS	–	–	2.93	–	–	0.92	–	–	NS

Table 7. Post-harvest soil properties (pooled mean of two years). Different alphabetical letters (a–e) indicate a significant difference between the treatments, while similar letters indicate that the treatments were on par.

use efficiency[23]. This method reduces the quantity of fertilisers needed, increasing nutrient use efficiency and minimising environmental impacts[24]. Fertigation also minimises nutrient leaching and allows for timely and crop-specific fertiliser application, thus reducing fertiliser losses[25,26]. Additionally, it helps in maintaining soil salinity at lower levels compared to traditional methods[27]. Water-soluble fertilisers are preferred for drip fertigation, as they prevent clogging in the drip lines and ensure proper dilution with irrigation water, ultimately benefiting crop production[28]. However, the higher cost of water-soluble fertilisers has been a barrier to adoption for some farmers, despite the numerous advantages it offers[29,30].

WUE and WP are essential metrics for evaluating water management practices in pulse crops, such as blackgram. WUE measures how effectively a crop uses water to produce biomass or yield, while water productivity connects the economic return (gross income) to the total amount of water used. These factors are critical because they reflect both the agricultural and economic efficiency of water use, particularly important in regions with limited water resources. The results showed that WUE and WP were significantly influenced by the treatments. Even though the same quantity of water was used in all methods, drip irrigation achieved the highest mean WUE and the highest WP compared to other irrigation methods. Micro-irrigation systems, especially drip irrigation, have been shown to significantly enhance both WUE and water productivity in blackgram. Drip irrigation delivers water directly to the root zone of the plants, minimising water loss due to evaporation and runoff. This precision ensures that water is used more efficiently and effectively, promoting better plant growth and higher yields[31]. For blackgram, the application of water-soluble NPK through drip fertigation has been associated with several benefits, such as the precise and timely delivery of nutrients directly to the plant roots supports better flowering and pod development. These ultimately result in enhanced nutrient availability, improving overall plant health and productivity, leading to increased yields. Research has demonstrated that using a 100% Recommended Dose of Fertilisers through water-soluble fertilisers in drip fertigation significantly improves WUE in blackgram. Studies have reported substantial increases in pod formation and overall yield when compared to traditional irrigation and fertilisation methods[32,33]. Improving water use efficiency and water productivity through advanced irrigation methods is crucial for sustainable agriculture, especially in water-scarce regions. Drip irrigation and fertigation are effective techniques for achieving these improvements in blackgram cultivation. By optimising water and nutrient delivery, these methods not only enhance crop yields and economic returns but also contribute to the sustainable management of water resources. Therefore, the adoption of micro-irrigation systems, such as drip irrigation and rain hose irrigation, is a promising strategy for improving the sustainability and resilience of pulse crop farming. Rain hose irrigation also offers good uniformity in water distribution, but it may not match the precision of drip irrigation. However, it still provides adequate coverage over a larger area compared to traditional methods. The rain hose system's nano-punching technology ensures even water distribution without clogging, helping maintain consistent moisture levels across the field. While both drip and rain hose irrigation systems improve water distribution uniformity and root zone moisture compared to traditional methods, the differences in yield can be primarily attributed to the precision and efficiency of water and nutrient delivery in drip systems. However, the cost-effectiveness, ease of installation and adequate performance of rain hose irrigation make it a viable and practical alternative, especially in resource-limited contexts.

Future research could focus on exploring the suitability of fertigation through a rain hose system of irrigation using straight fertilisers or minimising the use of water-soluble fertilisers to reduce costs and achieve higher net income. In addition to rain hose irrigation methods, newly emerging automatic plant irrigation systems based on hygroscopic materials and interfacial solar desalination have received increasing attention in recent years. These advanced techniques may also be explored further[34–40]. The application of hygroscopic materials could involve harvesting moisture from the atmosphere in the evening and watering the plants during the daytime. However, such technologies need to be tested and verified at the field level in agriculture.

Conclusion

Water availability poses a significant constraint in blackgram cultivation, and its production is severely affected without adequate irrigation, as moisture stress significantly limits yield. While farmers employ various micro-irrigation techniques, the investment and installation costs, particularly for drip systems, are often prohibitively high. However, the rain hose irrigation system emerges as a cost-effective alternative for blackgram cultivation in garden and dryland ecosystems. In this context, the current study aimed to assess the effect of different irrigation methods on blackgram growth, yield and profitability. Results from the experiment revealed that cultivating blackgram with the rain hose irrigation method, while adhering to existing agronomic practices, not only ensures better net profit but also maintains higher soil moisture levels, especially at depths of 10 and 20 cm. The ease of installation and the absence of clogging, owing to nano-punching technology for hole creation, make rain hose irrigation a practical choice for irrigating blackgram crops and facilitating adoption.

To conclude, the adoption of rain hose irrigation will result in higher growth, productivity, maintenance of soil moisture, water use efficiency, water productivity and profitability for farmers. Even though drip irrigation provides higher yields and nutrient uptake, the rain hose system offers several advantages, including lower costs and extended soil moisture availability. Cultivating blackgram with rain hose irrigation results in a 27.1% cost saving and a 15.32% higher BCR compared to drip irrigation. This method facilitates efficient nutrient solubilisation and root zone delivery, creating favourable microclimates for improved blackgram growth and yield. Additionally, adopting fertigation with water-soluble fertilisers via drip irrigation can enhance nutrient use efficiency and mitigate environmental impacts. However, the cost of water-soluble fertilisers remains a challenge for some farmers. In summary, choosing the right irrigation method, optimising nutrient management and considering cost-effective alternatives are key factors in achieving sustainable and profitable blackgram cultivation.

Data availability

All data generated or analysed during this study are included in this published article. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions
Conceptualization, supervision, methodology and formal analysis—S.M. and U.S., Original draft preparation—S.M.; V.M.B., S.M. and U.S. Data curation and analysis—S.M., S.V., S.P., V.G., M.R., A.P.S., M.K. and V.M.B.; Project administration, investigation; S.M., V.M.B. Writing—review and editing. S.M., S.V., S.P., V.G., M.R., A.P.S., M.K., V.M.B., S.M. and U.S. All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

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