Improved sprinkler irrigation layouts for smallholders

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Abstract: Pressurized irrigation systems are economically justifiable for medium- to large-scale farms, while fewer choices are available for smallholders. The current research work provides additional options for small plots, as the only income source for low-income farmers in poorer countries, which produce a considerable portion of the agricultural products in some regions of the world. In this research, two novel layouts of a semipermanent sprinkler irrigation system, namely, clock hand (CH) and corner pivot (CP) lateral designs, were designed for a lighter irrigation system to lower the cost requirement. The new techniques were based on a quadrant/full circle movement pattern of manually pivoting laterals, with no/shorter main pipe requirements, which causes a higher system efficiency. These retrofitted layouts were examined in different farms with areas of 0.20 hm^2, 0.81 hm^2, 1.62 hm^2, and 3.24 hm^2 in Guangxi, China. This study introduced, analyzed, and compared the layouts with the widespread traditional split lateral method on technical planning, components, implementation, operation details, size optimization, performance evaluation, and economic advantages. In comparison with the traditional system, CH and CP were found to be more user-friendly and cost-effective but slightly complicated in design with higher required manual work. The results revealed a distribution uniformity (LQ_{DU}) of 81.0% to 84.0% via the catch can method, lower capital costs (35.0%-45.0%), and lower annual expenses (6.5%-9.8%) for CP and CH, respectively, compared to the split lateral method. The 0.81 hm^2 and 1.62 hm^2 farms were found to be the optimum farm sizes for implementation of the new methods for a 25-year project time horizon. The outcomes of this experimental work can encourage small farm owners with limited capital to apply pressurized systems for efficient irrigation and water resource sustainability.

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1 Introduction

Although more than two-thirds of the accessible freshwater worldwide is used in the agriculture sector[1], 80% of the croplands are rainfed[2], and the remaining irrigated 20% produce approximately half of the required food for humans[3]. Remarkably higher water application efficiencies of pressured irrigation systems[4] compared to traditional methods[5] can lead to optimized water utilization, which is a key to saving finite water resources. Nevertheless, farmers are not keen to practically implement these systems due to costs that contradict the necessity of public contributions to sustainable development and food security. Furthermore, the lack of subsidies for irrigation systems combined with the imbalanced distribution of water resources results in the application of traditional low-efficiency methods. On the other hand, increasing population trends[6] drain more water from aquifers for food production. Taking into account the yield difference of the irrigated farms versus rainfed cultivation farms, which is 2-3 times higher for the former, applying new irrigation systems, is the best optimization solution.

Basically, there are three main categories of irrigation methods. Various traditional surface methods are still being applied with lower costs and efficiencies, in addition to manual process requirements. For low-slope plots that have sufficient water and manpower availability, methods such as a level basin or furrow can be exploited[7]. Where water is limited, low-pressure drip irrigation offers very high efficiencies and low costs with less manual work. Sprayers and drippers are trickle systems that maintain moist soil conditions around plants[8]. Sprinklers, as the third method, are a category of different techniques employed in a variety of conditions and adaptable according to the economic, technical, and geographical circumstances[9]. Systems such as center-pivot sprinklers, gun sprinklers, wheel-move systems, portable systems, permanent systems, and semipermanent systems

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are some examples that have been developed to meet different conditions.

Most of the current pressurized systems, economically and sometimes technically, are justifiable only for medium- to large-sized farms. However, a considerable portion of farms worldwide is cultivated by small estate holders who are not financially able to afford a pressured system. Analyzing the required components for the irrigation system shows that pipe length and diameter play the most significant financial roles[10]. Therefore, the hypothesis of the novel layouts offered here is indeed the integration results of ordinary semipermanent layouts with a center-pivot system movement pattern. If the new mechanism could reduce the required costs and successfully perform in the field, this would help small-scale farms have the advantages of a pressurized irrigation system as well as more sustainable water resource management[11], which would benefit society. Altogether, studies in this area are vital for ensuring the sufficiency of food production.

Hence, the current work 1) introduces and designs two new and efficacious sprinkler irrigation layouts for small plot holders; 2) technically analyzes their required criteria and components in detail to implement in small-scale farms; 3) evaluates the water distribution uniformity of the new methods; 4) economically analyzes and compares them with a traditional split (SP) lateral system in a 25-year time horizon; 5) identifies the optimum farm sizes (from 0.20 to 3.24 hm^2 which is equal to 0.5 to 8.0 acres) to effectively apply these light systems; 6) illustrates the overall advantages and disadvantages of these novel layouts. The outcomes of this research will help to expand the list of available options for end-users, in addition to further research potential for researchers in this area. This experimental study is useful for engineers, farmers, and decision-makers to select and design a pressurized system according to different needs and conditions[12].

2 Materials and methods

2.1 Study area

The experiment was conducted for four different farm sizes in the agricultural scientific and technological demonstration park of Guangxi Province, South China (23°14′N, 108°02′E). The site has a subtropical monsoon climate, an annual mean air temperature of 21.6℃, and annual precipitation of 1304 mm. The three layouts of SP lateral, corner pivot (CP) lateral, and clock hand (CH) lateral were designed for 0.20 hm^2, 0.81 hm^2, 1.62 hm^2, and 3.24 hm^2, and then the required components were obtained from a local market. Later, the systems were set up, and after implementation, the operation was performed in 2019 for one month each (i.e., April to May for SP, May to June for CH, and June to July for CP) to evaluate the performances.

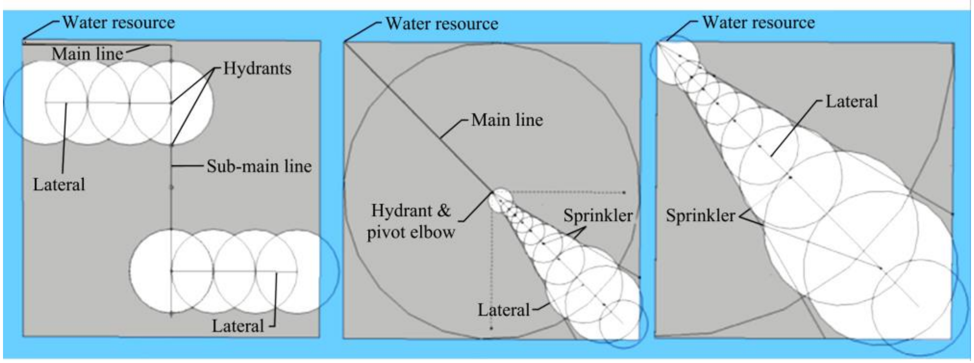
Finally, the evaluation and size optimization were carried out, and the capital and operation expenses, as well as incomes, were illustrated to assess the functionality of these systems through the obtained results.

2.2 The new system design criterion

The main hypothesis in this work is to combine a semipermanent irrigation system with a center-pivot irrigation system. Basically, in a semipermanent sprinkler technique (Figure 1a), the two (or more) split laterals are placed symmetrically along the main pipe and hand-carried lengthwise to complete one irrigation cycle[13]. Toward the pipe's end, a sufficient number of hydrants are provided to feed the laterals as per the number of lateral movements[9]. In this technique (unlike the permanent system), the number of laterals (and sprinklers/raisers) is minimized to reduce the system component costs. On the other hand, in addition to this system, the well-known center pivot is an advanced system that irrigates the farm automatically in a circular pattern (with the help of corner arms to maximize the covered areas). However, it is only applicable for large farms due to its expensive implementation and maintenance requirements. In this method, enough sprinklers/sprayers are installed on a rotating arm that moves around the plot automatically (usually very large plots) while irrigating.

Nevertheless, the combination of these two systems results in more efficient set-move layouts such as CP and CH. The two new techniques in this work are in fact semipermanent systems that imitate center-pivot transfer patterns, but manually. For the clock hand lateral design, as a set-move system for small farms (Figure 1b), the shortened mainline (compared to traditional semipermanent) delivers water to the center point of the farm. This technique can considerably reduce the length of the main (or submain) pipe. In the center, this pipe will feed a single lateral pipe that is equipped with a rotating pivot elbow that moves on a circle.

The lateral then will be hand-carried to the next section like a clock hand or a center-pivot system. By applying a pivoting lateral, the entire plot can be irrigated in a full cycle using fewer laterals. Moreover, since the number of laterals (and sprinklers/sprayers, consequently) has decreased, a smaller main-pipe diameter would be required. Likewise, in the CP lateral design (Figure 1c), the mainline is omitted entirely, and the lateral is directly connected to the water source via the pivot elbow, moving in a quarter. Corner arms in both methods are designed to completely cover the corners and amend the circular/quadrant pattern of the lateral movements. Figure 1 illustrates these three concepts virtually for comparison.



a. Split lateral b. CH c. CP

Note: CH: Clock hand; CP: Corner pivot.

Figure 1 Conceptualized split lateral, CH, and CP

In this experiment, for a loam soil type condition, with a 13 mm/h and 170 mm infiltration rate and water holding capacity[14], respectively, a maximum allowable depletion of 0.55, average evapotranspiration of 5 mm/d, and a system efficiency of 80%, the systems were designed. Wheat plants with a root depth of 120 cm were chosen, with a crop coefficient (Kc) of 1.2. The crop evapotranspiration (ETc) was computed based on the reference crop evapotranspiration (ETo) ETc = Kc ×ETo as 6 mm/day; therefore, the net and gross irrigation depths were obtained as 112.5 mm and 140 mm, respectively, which led to a 15 d irrigation cycle[15]. Other necessary information during the operation was as follows:

1) 5th April to 5th May, ETc: 3.67-3.95 mm/d, Temperature (T): 18.4 ℃-23.1 ℃, rain: 94.6 mm; 2) 10th May to 10th June, ETc: 4.86-6.00 mm/d, T: 23.1 ℃-26.3 ℃, rain: 152 mm; 3) 13th June to 13th July, ETc: 5.81-3.94 mm/day, T: 26.3 ℃-28.2 ℃, rain: 114.7 mm.

Although precipitation was sufficient for crop water requirements in some periods, since the research aimed to assess the new layout performances, system operation was ongoing.

The lateral distance and sprinkler radius were consequently chosen as a function of the watering cycle and required watering time to be completed. Thus, the entire farm can be irrigated. The sprinkler discharge rate (q) was calculated using Equation (1)[15].

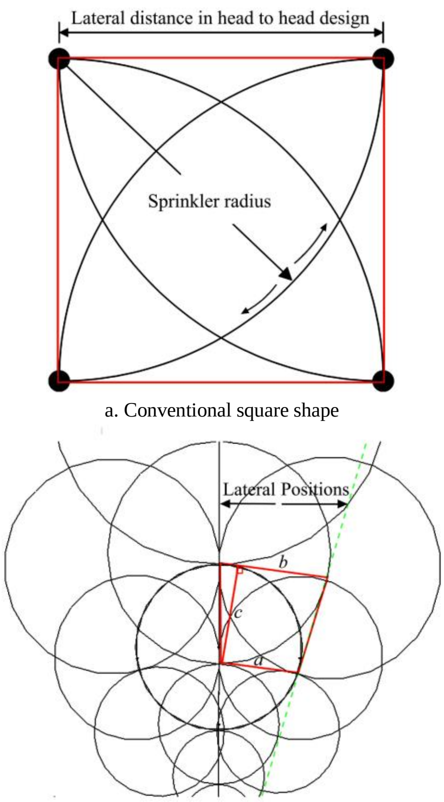
$$q = \frac{I \times S_l I \times S_m{}'}{3600} \tag{1}$$

where, q is the sprinkler maximum flow rate, L/s; I is the soil infiltration rate, mm/h; S_l is the sprinkler distance, m; $S_m{}'$ is the average lateral distance $((a+b)/2$ in m in which a and b are the shorter and the longer trapezium sides according to the Figure 2b) as it varies along the CH/CP lateral direction, m.

Additive discharge rates cover the trapezium shape overlapped area among four sprinklers in every 2 set-moves (set move means moving the lateral to the next position for watering) compared to the conventional square shape (Figure 2). The distance for the lateral transfer in each set-move is under the control of the utmost sprinkler radius. Once the last sprinkler is chosen, then the rest of the sprinklers' radiuses can follow according to the distance between the lateral movements. Each distance of throw fits into the two guidelines (lateral positions) with a smaller size toward the center to maximize the coverage. Taking the soil infiltration rate and manpower as the limiting factors, the outermost sprinkler radius was obtained, assigning the throw distances of the remaining sprinklers. Large sprinklers result in higher working pressure requirements, outflow rates, and pumps but lower working hours, and vice versa.

Corner catchers were utilized for this design to maximize the irrigated area. The extended arm applied in the corner was designed as two pieces separated by rotation elbows to enable them to be crooked toward the desirable directions to maximize the irrigated areas. To calculate the arm length, the space between the square corner and the circle circumference must be taken into consideration (Figure S1).

For both CP and CH layouts, constant-flow-rate sprinklers and sprayers were used, as the systems needed different discharge rates and distances of throw along the lateral pipe to avoid pressure surplus impacts on overirrigation. The various required radii cause different sprinkler distances on the lateral components[16]. The system discharge rate was accounted for as the total sprinkler/sprayer discharge rate working at the same time. However, for customization, the corner catcher arm is designed to work only 50% of the time[17]; therefore, an adjusted system total flow rate was considered. A spraying intensity of 11.1 mm/h and peak required irrigation time of 10.1 h/set-move (maximum twice daily) were accounted for in three layouts, which gave a value of 0.78 L/s/0.40 hm^2 (or per acre) for the hydro module. Supported by the above measures and taking into consideration a velocity margin of water in the pipes (maximum of 1.6 m/s and a minimum of 0.6 m/s), the required diameters (telescopic design) and lengths of tubes were quantified. The amount of friction loss was calculated based on the famous Hazen-Williams formula[18]. To obtain the total dynamic head (TDH) of each system, the highest-sprinkler working pressure, the raiser required head (1.5 m), as well as an additional 10% head for fittings and water resource elevation, were considered. Finally, the amount of energy consumption for pumps in kilowatts was computed[19].



Note: a is the shorter trapezium side; b is the longer trapezium side; c is the perpendicular from a to b.

Figure 2 Conventional square shape and trapezium overlapping pattern of four sprinklers

2.3 Component analysis, implementation, and operation requirements

According to the site characteristics and system designs, layouts were developed[20]. The number of basic required components in this study is listed in Table 1. The distances mentioned in the table for the new layouts are the distance ranges of the applied components (sprinkler or sprayers used). PVC tubing was used in 9-12 m pieces to ease the manual transfer process. Moreover, PVC tubes were applied due to the possibility of sprinkler installation with additive distances on this type of pipe, as aluminum pipes for irrigation have fixed outlets and hence are not suitable for customization or riser installation at different distances. Pressure regulators were installed for sprayers that required low pressure (two in this case) at the beginning of the line to keep the pressure of those sprinklers/sprayers low. In such occasions, market limitations might assign specific types of sprinklers that impose additional costs.

For the corners of the plots, a detachable corner arm was designed, as two foldable independent pieces, equipped with shut-off valves to detach from the lateral unless at the corners, where they operate. The same process was followed for both CH and CP layouts except that for CP, water was conveyed from the water source to the center of the farm through the main or the submain pipe to feed the lateral pipe, while CH technically had no main pipe. The other required components, such as the pump and power unit, tank and filter, pressure gauge, air valve, hydrant, elbows, and fittings, were provided according to the plot size and consequently the system size. Layouts were set up on farms at the Lijian irrigation test center of Nanning city after the components were transferred and installed according to the above-designed layouts. Figure S1 shows a representative concept for CH.

Table 1 SP, CH and CP systems designing criteria / component for different farm sizes

Item	SP				CP				CH			
Farm Size/hm^2	0.2	0.81	1.62	3.24	0.02	0.81	1.62	3.24	0.2	0.81	1.62	3.24
Sprinkler required pressure (bar)	3	3	3	4	2-3	2-3	2-3	2-4	2-2.5	2-3	2-3	2-4
Sprinkler per second discharge rate /L s^{-1}	0.14	0.41	0.89	1.36	0.02-0.3	0.02-0.3	0.014-0.8	0.014-0.9	0.014-0.1	0.020-0.3	0.014-0.7	0.018-0.8
Distance of the sprinklers/m	6.8	11.5	17	21	2.0-11	2.0-11	2.0-14.7	2.2-20	1.4-5.8	2.7-11	2.3-14	2.1-20
Distance of the laterals/m	6.8	11.5	17	21	11	11.7	17	20	5.8	11.7	14.2	20
System total flow rate/L s^{-1}	1.00	3.26	7.13	12.24	1*	2.18*	4.75*	7.34*	0.29*	1.09*	2.04*	3.93*
TDH/m	39.7	37.8	44.7	55.5	40.9	45.5	43.3	57.7	33.1	44.6	43.6	53.5
Number of sprayers and sprinklers	7	8	8	9	10	18	21	28	10	10	10	13
PVC tube in different sizes/m	113	216	300	424	72	142	195	283	75	136	178	259
No. of hydrant valves	8	9	9	10	1	1	1	1	1	1	1	1
No. of fittings (elbow, coupling)	55	72	79	95	55	84	98	102	53	58	65	83
0.6m deep ditch to bury the pipe	71.6	133	181	260	0	0	0	0	34	65	90.6	127
Number of set move/revolution	7	8	8	9	7	12	12	15	24	24	28	28
Number of working hours in year	462	528	528	594	462	792	792	990	1584	1584	1848	1848
Energy used per year/kW	256	913	2356	5653	264	1100	2282	5869	213	1079	2300	5439
Required water per year/(1000 m^3)	1.66	6.2	13.55	26.17	1.66	6.22	13.54	26.16	1.65	6.27	13.57	26.15

Note: *Average discharge rate of the system considering the corner catcher will work 50% of the time. SP: Split lateral; CP: Corner pivot lateral; CH: Clock hand lateral. The same as below.

The implemented systems were operated for a month each at the site. After watering each slice of the farm by the lateral, the pump was shut off, the pipes were detached to be transferred to the next position manually, and the next portion was irrigated until a full cycle was completed. Although the experimental site was not windy, to minimize the wind impacts on the water distribution, a Y-branch can be designed at the beginning of the lateral direction so that the pipe could be shifted against the wind direction according to its speed in windy situations (as shown in Figure S1), especially for sprayers that are relatively sensitive to wind.

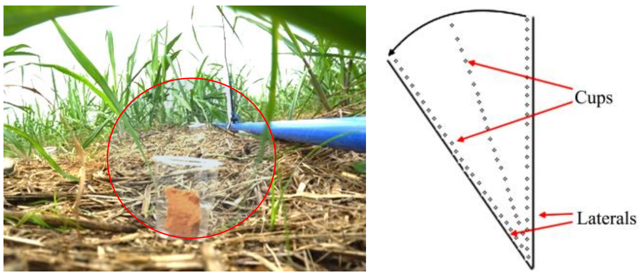
For accuracy, flags were placed in the farms according to the system movement patterns (on a virtual ring) and the designed lateral distances in each farm for CP and CH to specify the lateral directions for each set-move (Figure 3). Moreover, the elbows were applied on the corner arms, so the pipes (the 2 pieces of the corner arm) could be rotated up to 360° in different directions as needed (Figure S1).

Figure 3 Flags applied to specify the lateral directions

2.4 System performance evaluation method

The catch can method was used to measure the water application efficiencies via the low quarter distribution uniformity (DU_{LQ}) equation[21,22]. In this method, the quantity of water collected in the cans was recorded, and the dimensionless DU value was computed as the ratio of the average lowest quarter to the average of all the values measured. Light plastic cups (with a small stone inside) were placed at designed distances between the lateral movements. The sprayed water on those spots of the irrigated circle around each sprinkler was collected under various operating pressures for DU evaluation.

The distribution uniformity experiment was repeated for two runs per treatment (30 min each). The water content of each cup was then poured into a beaker to ease the water volume measuring process in mm/hr. Radially, 3 cups (Figure 4a) were located, one at the center and the other two toward the end of the irrigated circle radius every meter (as shown in Figure 4b).



a. Cups placed on the farm

b. DU Distribution uniformity measurement as per the pattern

Figure 4 Cups placed in the farm for DU measurement as per the pattern

Identifying under/overirrigation spots in each layout, which may not be observationally identified, is an advantage of this test to take the necessary actions (such as sprinkler replacement) wherever required. Additionally, for one of the treatments, the entire area between the four sprinklers was carefully examined to evaluate the 3D depth of the water distribution.

In addition, the number of working hours for each system was calculated as a point of comparison. This not only impacts the system's overall energy consumption but also influences the manpower and manual work requirements of different sizes. User-friendliness and convenience in working with CP and CH compared to SP were other criteria to consider during the experiment and evaluation process.

2.5 Economic analysis method

Component prices, transfer, implementation, water and electricity fees, and other requirements were calculated based on local rates[23,24], in which the water cost was 105 RMB yuan/(year 0.4 hm^2 or per 1 acre area) and electricity was 0.5 RMB yuan/kW. As per system requirement, the present values (Pvs) of capital and annual expenses were calculated according to a 25-year project planning horizon[25]. The benefit-to-cost ratio (BCR) and net present value (NPV) methods were applied for more profitable system recognition, followed by break-even point (BEP) evaluation, which was calculated at a specific internal rate of return (IRR) of 3.3%. The annual incomes for the targeted period were accumulated as their Pvs. It was computed as per the latest average price of the local market in China and converted into USD based on an approximate exchange rate (1 USD ≈ 7 RMB Yuan). The Pvs of both costs and incomes for the targeted horizon, taking into account 3.3% annual interest, were obtained via Equation (2)[26] below for each year and then accumulated as total Pv:

$$\mathrm{Pv} = \frac{C}{(1+i)^t} \tag{2}$$

where, Pv is the present value; C is the amount that the investor will spend or earn in the future; i is the applied rate of interest, %; t is the number of years.

Later, the NPVs were computed as the difference between the present value of the incomes, subtracting the present value of the costs (inflow-outflow) of each project for the intended period. Additionally, the BCR was calculated to demonstrate the ratio of the project benefits to its costs in monetary terms[27]. This indicator shows the return of investment (ROI) for each system compared to its costs. Operational limitations, such as manpower requirements, due to the different system working hours and economic indexes (IRR and BEP), were applied to specify the best farm size for each layout and to financially control the application possibility of the new systems. The aim was to determine the time required for the NPV to reach 0 for each project. This duration, from there onwards, indicated that the NPVs were positive and the amount of profit will be above 0, while all the costs had already been paid. This observation merits concern for farmers, especially when a small farm is the only income source for them. Therefore, investors can consider the time required for ROI of the project because the first years after the new system implementation will have the highest financial pressures.

3 Results and discussion

3.1 Design, operation, and component comparison of the three layouts

In terms of design, both new systems have a similar but slightly more complex process than the traditional set-move layout. The additive distance of the throw along the lateral direction, as well as the circular/quadrant movement pattern, requires a different set of functions to be taken into consideration. This causes a new pattern of coverage among every 4 sprinklers that form a trapezium; therefore, the water distribution pattern would also be affected. Due to the fewer laterals but more set-moves in one revolution (as listed in Table 1), the unique scheme of the new layouts causes higher working hours and manpower requirements. In particular, CH has a shorter lateral span than CP. The number of set-moves (and working hours, consequently) can be controlled by the utmost sprinkler watering diameter, which is also a function of the soil infiltration rate.

This increase in working hours for the two new layouts (Table 1) can be justified based on the fact that, for small estate holders (up to an optimum farm size), a higher income is worth additional manual work if it is manageable. However, if external manpower would be required, then the implementation of these systems may not be practically/financially justifiable. Nevertheless, these changes in the layouts will not impose further energy consumption or higher water utilization for the new techniques compared to the conventional SP. The relatively small pump and power unit and the low outflow rate of the systems during the watering season result in the same total amount of water and energy requirements.

Compared to SP, both CP and CH needed fewer components (pipe, fitting, hydrant) and consequently were lighter systems. The pipe burying requirement for CH was half that for SP, as the pipe could be laid from the water source to the farm center directly, while CP did not require any trenches to bury the tubes since the starting point (at the corner) was also the water source. For the pipes, CP needed a 34% shorter pipe length than SP, while CH needed a 38% shorter pipe length than SP. Between 8 and 10 hydrant valves (depending on the farm size) were used for SP, but the new systems needed only one hydrant. This enhancement will reduce the amount of work required to transfer the components to the site and implement and maintain the system. For the applied fittings, CP needed 13% fewer fittings than SP, and CH needed 20% fewer fittings (with smaller sizes). Additionally, the amount of manual work (in one set-move) was comparatively less in the new systems than in SP since fewer pipes required detaching, transferring, and attaching to irrigate the next slice, and traveling from one side of the farm to the other side is not required. Thus, these newly developed layouts are user-friendly and easy for farmers to work with.

3.2 Distribution uniformity evaluation of the new layouts

The DU_{LQ} values of all three layouts were measured quantitively in the field. The water distribution in mm for the new systems is graphically presented below (Figure 5). The sprinklers were placed at different distances toward the end of the lateral pipe. Moreover, the bell-shaped rainwater around each sprinkler was complemented by the front and the behind sprinkler/sprayers. The total collected water line in Figure 5 shows how much water was poured into each spot. On average, an 84% uniformity rate of distribution was obtained for the CH system, followed by 81% for the CP system and 82% for the SP system, which was a reflection of an efficient irrigation pattern. Although it was slightly uneven (almost 45% coverage from one side and 55% from another), an acceptable water DU for the sprinklers in the area between the radial legs of the new layouts was achieved during the experiments. Similar studies on DU measurement for sprinkler irrigation have attained different results, such as 62%[28] and 84%[29]. The results show a comparatively good uniformity in the entire plot (on average) that presents the capability of CH/CP to provide an adequate water depth at each point. The irrigated circle around a single sprinkler/sprayer had a normal distribution graph (bell-shaped) in response to a satisfactorily applied pressure. Technically, having a low/high water pressure in the system will result in large/small droplets that cause over or under irrigated spots in the field. The DU for new systems in 3D is graphically shown in Figure 6 in a typical area overlapped with 4 sprinklers.

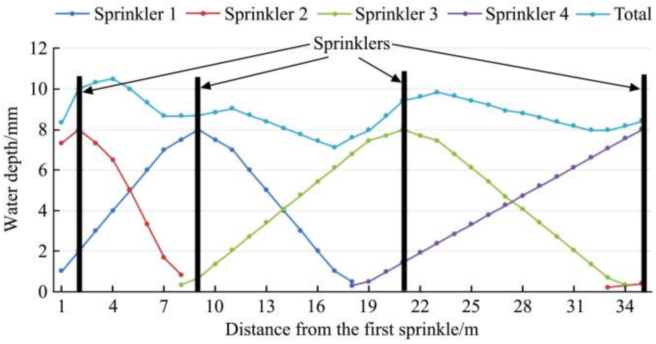


Figure 5 Water distribution pattern of every 2 sprinklers in new layouts (CP/CH)

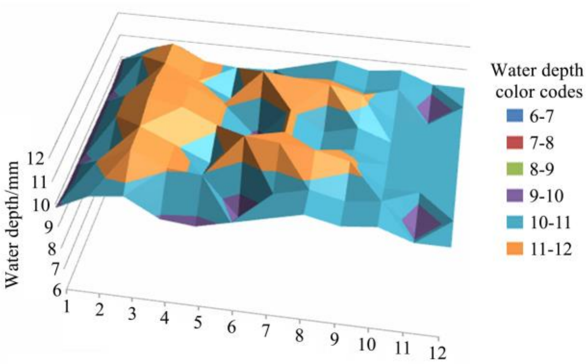


Figure 6 A 3D water distribution pattern of CH/CP in 4 sprinklers overlapped area

The total irrigated depth of water around an individual sprinkler was slightly lower on one side due to different radii of overlapped sprinklers which was 6%, on average. The lowest collected depts of water were seen to be in spots by the cross-section of the irrigated circles toward the edges, while the areas closer to the raisers were receiving higher amounts of water.

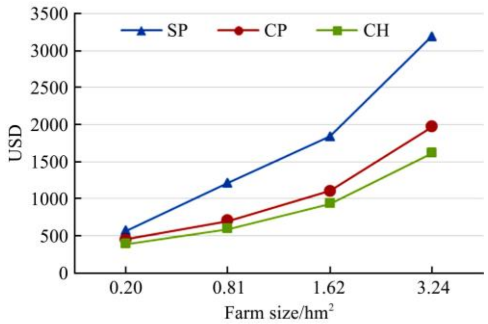
3.3 Economic analysis

The results show how the capital and annual costs of new layouts were reduced compared to the SP (split lateral) layout for different farm measures. The system component and implementation costs, as well as incomes, might differ in various countries or at different times, yet as a point of comparison, the ratios will justify the hypothesis. The system capital and annual expenses are listed in detail below (Table 2) for all 12 treatments. Based on the outcomes, the required expenses (capital and annual) among the 3 layouts can be classified as CH (the lowest), followed by CP and SP. A 35% lower capital cost was obtained for CP compared to SP as an average of all farm sizes, while that of CH was 45% less than that of SP. The most influential factor in capital cost decrement was pipe cost with more than 70% weight. The remaining balance of items such as burying cost, pump and power unit, implementation & transfer, hydrants, and fittings had far fewer impacts. Lower flow rates (35% lower for CP and 69% lower for CH compared to SP) require a smaller pump and power unit. However, employing additional laterals will reduce this gap and, as a result, the economic advantages. Shorter tubing (and smaller diameters) in general will need fewer more cost-effective fittings. As presented for the capital costs (Figure 7a), the gap between the new layouts and SP expands with increasing farm size. As an example, for the new systems, on average, when the farm size is just 0.20 hm^2, the required capital cost is 26% lower than for the SP system, while for the largest plot, the capital cost is 44% lower.

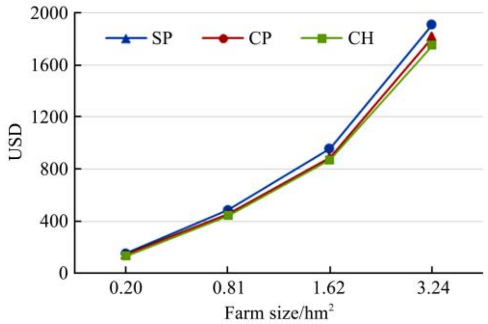
With regard to annual operation cost reduction, the cost of CP was 6.5% lower than that of SP, and that of CH was 9.8% lower (Figure 7b). Here, the repair and replacement cost, as well as annual interest, followed by insurance and taxes, with 37%, 37%, and 28% weights on average, respectively, had the highest impact. The other items had minimal influence. However, most of these items (except energy and water) are heavily dependent on the amount of the system's capital cost. The effects of CP and CH on water utilization and energy consumption were negligible because first, all the systems must provide enough/equal depth of water for the farms, and second, the low system discharge rates were compensated by the number of working hours.

Table 2 Systems cost comparison for different farm sizes in USD

Item	SP				CP				CH			
Farm size/hm^2	0.20	0.81	1.62	3.24	0.20	0.81	1.62	3.24	0.20	0.81	1.62	3.24
Total required pipe cost	141	611	1033	1881	96	249	519	957	68	195	397	789
Sprinklers & sprayers	25	50	59	94	36	58	66	101	18	26	38	52
Hydrant valve fee	21	38	48	56	2	4	5	6	2	4	5	6
Fittings	20	35	41	69	19	28	40	64	18	23	22	46
Others (tank, gauge, etc.)	157	188	231	370	137	162	208	345	126	140	184	255
Main pipe burying cost	35	56	90	127	0	0	0	0	18	29	46	68
Pump and Installation	100	115	145	250	100	115	130	230	85	95	115	145
Installation & transfer fee	70	120	195	340	60	90	140	270	55	85	130	255
Total capital cost/USD	569	1213	1842	3187	450	706	1107	1972	390	597	937	1616
Energy cost per year	18	65	168	404	19	79	163	419	15	77	164	388
Maintenances (3.3%)	19	40	61	105	15	23	37	65	13	20	31	53
Insurance and Tax (2.5%)	14	30	46	80	11	18	28	49	10	15	23	40
Annual interest (3.3%)	19	40	61	105	15	23	37	65	13	20	31	53
Yearly water cost	8	28	61	118	8	28	61	118	7	28	61	118
Farm machinery costs	40	150	310	626	40	150	310	626	40	150	310	626
Seed, fertilizer & pesticide	35	130	250	470	35	130	250	470	35	130	250	470
Total annual cost/USD	153	484	957	1908	142	451	885	1813	133	439	871	1750
Total annual income	373	1492	2984	5968	364	1455	2909	5819	364	1455	2909	5819
NPV/USD	3156	15 821	32 397	65 393	3296	16 255	33 081	65 698	3509	16 557	33 488	67 119
BEP/year	3	2	1	1	3	1	1	1	2	1	1	1



a. Capital



b. Annual

Figure 7 Capital, and annual cost comparison in USD for SP, CP & CH systems in different farm sizes (0.20 to 3.24 hm^2)

It is clear in Figure 7b that the annual cost differences between the new layouts and SP are much smaller than the capital cost gaps. Additionally, when the farm size increases, the annual to capital cost ratio also increases. As an example, for 0.20 hm^2 farms (on average), the ratio of the annual cost is just 30% of the capital, while in contrast, it increases to 81% for the 3.24 hm^2 plots. Unlike the capital cost, however, the annual cost requirement in percentage for CP and CH decreases when the plot size increases. When the farm size is small, the CP and CH annual costs decrease by 9.7% on average. The decrease in annual costs plateaued when the plot area expanded further, as the systems had only a 6.6% operational cost decrease on the 3.24 hm^2 farms.

The Pvs of both costs and incomes and then the NPVs for all twelve treatments were calculated. Considering the average annual wheat yield in China[30] at 5 t/hm^2, with 2 t/hm^2 straw production for irrigated farms and 50% of these amounts for the rain-fed parts of the farms, incomes were obtained. In this comparison, the same yield rates of the irrigated areas for all 3 layouts were considered due to the similar LQ_{DU} results for the examined plots. The wheat price in China accounted for 2300 RMB yuan/t (Approximately equal to 329 USD), and the straw price accounted for 700 RMB yuan (100 USD)/t, which gives a total annual income of 1845 USD/hm^2. Moreover, 95% watering area coverage for CH and CP layouts was taken as the fully irrigated area to assess income. The remaining 5% of the farm was considered rainfed.

CH has the highest NPV, followed by CP and ordinary SP (Table 2). In general, the NPV difference between CH and SP is 5%, and between CP and SP, on average, the difference is 3% in 25 years. Furthermore, when the farm size increases, the difference between the systems decreases, but in contrast, the highest NPV difference is observed for the 0.20 hm^2 farm. This result demonstrates that the new methods are more suitable for small farms than conventional techniques.

Since the NPV itself will not show the amount of investment for an individual project, the use of NPV as a point of reference is advised to be applied only for projects on the same scale. Therefore, in most cases, a combination of NPV and BCR presents a more descriptive picture for investors to evaluate how profitable each option is. In this study, the BCR values sharply increased when the farm size increased from 0.20 to 0.81 hm^2 due to the cost per unit reduction rule of thumb (Figure 8). The BCR continued to increase gradually from 1.62 to 3.24 hm^2 and almost maintained the same level up to 3.24 hm^2.

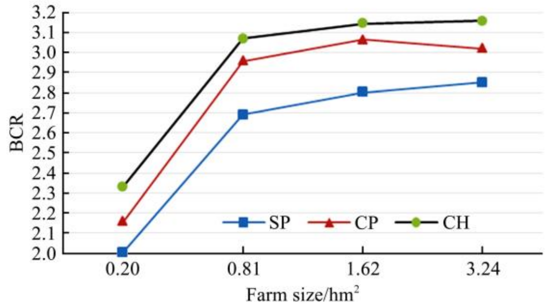


Figure 8 BCR for SP, CP, and CH during 25 years, when the farm size increases

As shown in Figure 8, the minimum BCRs were observed for the SP system, while for CP and CH, the BCRs were 8% and 13% greater, respectively. This result indicates that implementing new layouts will result in earning the same income at lower costs compared to SP. The results show that among the four plots, the greatest BCR values were obtained for the 0.81 hm^2, 1.62 hm^2, and 3.24 hm^2 plots with a gradual increase (negligible difference of 3.0% to 4.5%), followed by the 0.2 hm^2 plot.

3.4 Optimized farm size for the new layouts

Outcomes revealed that the BEPs at a 3.3% IRR for the 0.2 hm^2 farms are 2-3 years, while for the rest of the farm sizes and layouts, an IRR of only 1 year with a similar pattern (except the 2.00 hm^2 SP) was obtained. The BEP results (in years are presented in Table 2. This means that the farmers can only recover the initial expenses after 2-3 years in the smallest size (0.20 hm^2); however, for the rest of the plots after the first year, the expenses are all paid, and the project NPV will be positive from that point onwards. Additionally, it was found that none of the three methods seems to be suitable for 0.2- hm^2 farms due to their relatively long ROI period. In other words, this sized farm might be less than the minimum area for a pressurized irrigation system, as the income would not easily pay the costs until after 2-3 years. However, for larger farms, a lower BEP will have a shorter time required for farmers to return the invested money. This is an important advantage, particularly for small estate holders when the farm is the primary source of income, as the farmers will suffer financial stress at the beginning of the project before recovering, especially with the absence of subsidies. Hence, relatively cost-effective systems with a short BEP would be preferable alternates.

On the other hand, the total yearly working hours of the systems (Table 2) on average were 44% higher for CP and 3.2 times longer for CH than for SP. For smallholders, it was assumed that the manual work required for the system operation would be performed by the landowners since hiring laborers for smallholders is not economically possible. This observation indicates that for relatively large farms (i.e., 3.24 hm^2) when manpower is not consistently available or insufficient, employing laborers will impose relatively large operational costs that make both of the new systems (or at least CH) unjustifiable. However, adding the second lateral CH can reduce the working hours by half but provides fewer benefits. Altogether, in terms of optimum scale, the best feasible and economic size among the tested options was found to be the 0.81 hm^2 farms (CP and CH) and then the 1.62 hm^2 farm (CP) for the new systems. While CH is economically preferable, considering the manpower requirements, the farmer can choose between CP and CH based on their available resources and services.

4 Conclusions

New techniques can help optimize costs and provide more economical options for small farms to implement pressurized irrigation systems. In this study, two novel irrigation layouts were introduced, designed, implemented, operated, technically analyzed, and economically compared with their traditional origin (split lateral semipermanent). The new layouts were found to be easy to use, lighter, less expensive, and suitable for small plots but relatively complicated to design with higher manpower required. The optimum size has been specified as 0.81 and 1.62 hm^2, as these systems are designed for small-scale farms. The BCR, NPV, and BEP were applied to analyze the capital/annual costs and incomes for 25 years. Practically, the feasibility of both new systems was tested, and the applicability of the new layouts was confirmed by the results. The performance of these layouts was assessed based on the DU_{LQ} method, and acceptable water distribution uniformity of 81% to 84% was achieved. More manual work and a greater system working time but the same amount of water and electricity consumption with lower capital and operational expenses (35.0% and 45.0% capital, for CP and CH, respectively, and 6.5% and 9.8% operational for CP and CH, respectively) were observed for CP and CH compared to SP. These lower capital costs are mainly due to fewer pipes and lower annual fees, mostly owing to the lower maintenance, taxes, interest, etc., of the new methods. NPVs were 3.0%-5.0% higher for CH and CP than for SP, while BCRs were 8.0%-13.0% higher for CH and CP than SP on average. Except for the 0.20 hm^2 farms for 2-3 years, the BEP for the rest of the sizes was just one year. In addition to promoting pressurized irrigation systems, the outcomes of this study can provide insight into the experience of these methods. Moreover, this study will provide guidelines for smallholders and engineers in irrigation system selection decision-making.

Acknowledgements

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Appendix

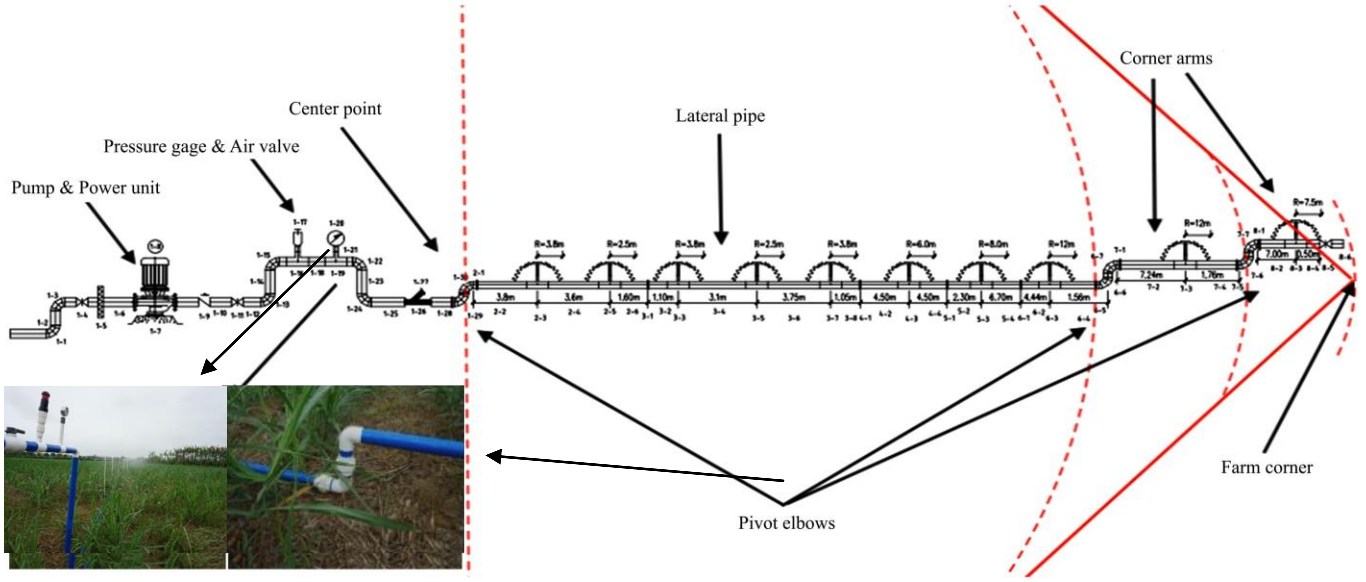

Figure S1 Schematic clock hand lateral at the center of the plot with the foldable corner arm