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Research article

Evaluating the adoption of irrigation technology in a well-irrigated winter wheat - summer maize cropping system

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A R T I C L E I N F O

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A B S T R A C T

Determining suitable irrigation technology is of paramount for promoting water-saving agriculture, particularly for winter wheat-summer maize rotation system in well-irrigated regions. To optimize and assess the efficacy of various irrigation technologies (specifically, semi-fixed sprinkler irrigation, walking sprinkler, semi-automatic buried telescopic sprinkler irrigation, thin-soft spray tape irrigation, drip irrigation, self-driven winch sprinkler and manually moving spray gun irrigation, marked as A, B, C, D, E, F and G) applied in south central North China Plain, we first conducted an economic analysis for the winter wheat-summer maize rotation. Subsequently, employing a comprehensive set of 20 indicators spanning economic, societal, technological, ecological, and resource aspects, we employed a TOPSIS model with integrative weighting approach using "AHP + Entropy". We also employed principal component analysis and the Sankey diagram method to explore characteristics of different irrigation techniques and indexes. Irrigation mode E, conserving energy by 63.19% compared to mode B and offering labor savings five times greater than the mode D. The highest economic benefit for the rotation system was observed with the mode C, resulting in a 25.26% increase compared to the mode G. The top three irrigation modes based on scores were D, G, and E, with scores of 0.532, 0.490, and 0.474, respectively. The Sankey diagram revealed distinct preferences among different agricultural entities for specific irrigation modes. For specific stakeholders, we recommend irrigation modes D, G, F, and B for small farmers, large and specialized family businesses, family farms, and farmer cooperatives, respectively. In conclusion, our findings provide valuable scientific support and recommendations for the practical application of irrigation technology in agricultural production.

1. Introduction

Groundwater serves as the primary water source for nearly half of irrigated agriculture. However, it is a cause for concern that millions of these wells, which are used to extract this vital groundwater resource, are at risk of running dry [1]. The North China Plain

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(NCP) holds significant importance as a production base for winter wheat and summer maize. This region boasts extensive acreage, flat topography, and fertile soil. However, the dominant cropping system in this area consumes a substantial amount of water, ranging from 700 to 1000 mm yr^{-1}, significantly surpassing the annual average precipitation levels of 500–600 mm [2]. Adding to the challenge, a considerable 60–70% of the annual rainfall is concentrated during the summer maize growing season, typically occurring from July to September. This uneven distribution of rainfall results in severe water deficits during the winter wheat season, where approximately 70% of its water demand rely on groundwater irrigation [3]. The over-exploitation for groundwater for agricultural irrigation has raised widespread concerns. This unsustainable practice has led to the rapid depletion of groundwater tables and has given rise to associated environmental issues [4,5].

China has undertaken substantial efforts to address its regional water resources crisis, exemplified by the implementation of nearly 10 billion cubic meters of ecological water replenishment through The South–North Water Transfer Project in areas where water is imported. Data has shown that, in general, the groundwater table ceased its decline and began to rebound after 2014. However, it's important to note that the deep groundwater levels in urban and agricultural areas have exhibited differential trends. In most agricultural areas, the decline in groundwater levels has persisted [6]. At present, groundwater remains the primary water source for agricultural irrigation in the NCP. Various water-saving irrigation technologies, including drip irrigation, sprinkler irrigation, hose micro-sprinkler, and border irrigation, have been made available in well-irrigated areas [7]. It's worth noting that farmers have often resorted to passive acceptance and blindly followed conventional practices when choosing and utilizing water-saving irrigation technology. This tendency can be attributed to the mandatory construction of farmland water conservancy projects and limited knowledge about water-saving irrigation methods. As Blanke et al. [7] concluded, Chinese farmers are more likely to adopt water-saving technologies when provided with appropriate incentives, information, and the means to overcome collective action constraints through data collection and informed decision-making. Hence, the judicious selection of water-saving irrigation technology, tailored to the region's economic development level, production scale, and management systems, holds paramount significance in effectively utilizing the limited groundwater resources available.

Irrigation costs increased rapidly with the advanced agricultural mechanization levels and highly intensive land management. Simultaneously, new irrigation technologies has gradually reshaped traditional irrigation practices in agricultural production. In previous studies, researchers have undertaken optimized layout and hydrodynamic analyses of drip irrigation networks, achieving precise control over field crop irrigation [8]. Furthermore, Fang et al. [9] suggested that the basin irrigation method proves to be more economically efficient when compared to tube-sprinkler irrigation, pillow irrigation, and drip irrigation. Their analysis, which considered the impact of various irrigation levels on crop yield, economic returns, and water use efficiency, supported this conclusion. Nevertheless, sprinkler and micro-irrigation methods, known for increasing crop productivity while allowing for precise and eco-friendly irrigation application, have demonstrated their effectiveness across a range of crops, including wheat, cotton, maize, and vegetable crops [10,11].

As previously mentioned, the choice of an evaluation framework and methodology is heavily contingent upon the specific characteristics of the irrigation system in question and the intended purpose of the evaluation [12]. In the subsequent research, fuzzy set theory has been employed to enhance and refine irrigation performance assessment [13,14,15]. Other methodologies, including principal component analysis and extension evaluation method [16,17], projection pursuit method and fuzzy comprehensive evaluation method [18,19], as well as the neural network method, TOPSIS method, and grey correlation method [20–22], have also been applied to assess irrigation performance. Among these approaches, the TOPSIS method, originally developed by Onar et al. [23], has gained widespread recognition and proven to be highly effective in the evaluating irrigation districts [24,25]. Scholars predominantly employ the TOPSIS method to in the realm of multivariate analysis and evaluation [26]. This method boasts a straightforward calculation principle and drivers results that are both intuitive and reliable, without imposing specific constraints on the data pertaining to the object of evaluation.

The core of the TOPSIS model is to determine the index weight, and the analytic hierarchy process (AHP) offers a versatile and straightforward statistical method that comes highly recommended for use in the evaluation of irrigation organizations [27]. Sun et al. [22] effectively established an evaluation index system by applying an improved version of AHP in the Huang-huai-hai river basin in the northern China. Furthermore, Banihabib and Shabestari [28] ingeniously combined the strengths of the modified technique for order preference by similarity to ideal solution (MTOPSIS) with AHP methods to prioritize strategies for agricultural water demand management (AWDM). They selected indexes from various domains, including water-saving administrative management, engineering management, water use management, and operation management, to construct an evaluation system for the level of water-saving irrigation management [29].

From the research mentioned above, a notable observation emerges: the method used to determining index weights has tended to be either overly objective or excessively subjective, often lacking a balance subject-object perspective. In the existing body of literature, the selection of evaluation criteria has exhibited a distinct inclination toward economic and resource-related factors, often neglecting the inclusion of certain criteria that are more challenging to quantify but intimately linked to irrigation practices. These overlooked criteria encompass aspects such as farmers' preferences for water-saving equipment and the compatibility between irrigation systems and crop cultivation techniques, among others. Furthermore, a recurring issue has been the excessive emphasis on infrastructure construction, coupled with a relative neglect of management standards, leading to a deficiency in precise assessments. This imbalance has, in turn, contributed to blind construction effort and diminished the overall efficiency of equipment utilization. Consequently, it becomes imperative to conduct a comprehensive evaluation of the applicability and extension of water-saving irrigation technologies, particularly in regions that are already well-irrigated.

In this study, we focused on the Xuchang high-efficiency water-saving irrigation experimental area (referred to as XCA), situated in the South Central North China Plain. Our research commenced by conducting an analysis of the economy benefits associated with the winter wheat-summer maize rotation. Subsequently, we adopted a holistic approach encompassing economic, societal, technological, ecological, and resource-related aspects to optimize the choice of irrigation technology. This optimization process was facilitated by constructing a TOPSIS model employing an integrated weight methodology that combines the "AHP + entropy" theory, thereby accounting for both subjective and objective factors. To further enhance our understanding, we delved into the intrinsic relationships between different evaluation indices and assessed their contributions to the first and second components using principal component analysis (PCA). Our study pursued four primary objectives: (1) to evaluate the economic advantages of commonly employed irrigation technologies in agricultural production; (2) to quantitatively determine the weights of various evaluation indices and construct a comprehensive model incorporating five dimensions: economic, societal, technological, agro-ecological, and resource considerations; (3) to identify the key components influencing the selection of water-saving irrigation methods through PCA, analyzing seven irrigation modes and twenty evaluation indicators; (4) to provide recommendations to guide governmental decision-making and assist different agricultural entities in selecting appropriate irrigation technologies.

2. Materials and methods

2.1. Region description

Field experiments and questionnaire surveys were conducted at well-irrigated region in XCA (33°42' – 34°24′ N, 113°03' – 114°19′ E) from 2019 to 2022, which has a total area of approximately 527.1 km^2 and an average elevation of 79.6 m above sea level (Fig. 1). The predominant soil type in the research region is characterized as damp sandy loam, while the climate falls within the category of a warm temperate continental monsoon. Over the long-term period from 1992 to 2022, the annual average precipitation is 697 mm, with a notable concentration of 55–65% occurring between June and September. It's worth noting that this precipitation exhibits an extremely uneven spatial and temporal distribution. The annual average temperature is 14.7 °C, and the sunshine duration is 2183 h. The winter wheat-summer maize cropping system was employed and irrigated using a combination of sprinkler and micro-irrigation technologies. These irrigation methods encompassed semi-fixed sprinkler irrigation, walking sprinkler, semi-automatic buried telescopic sprinkler irrigation, and thin-soft spray tape irrigation, among others.

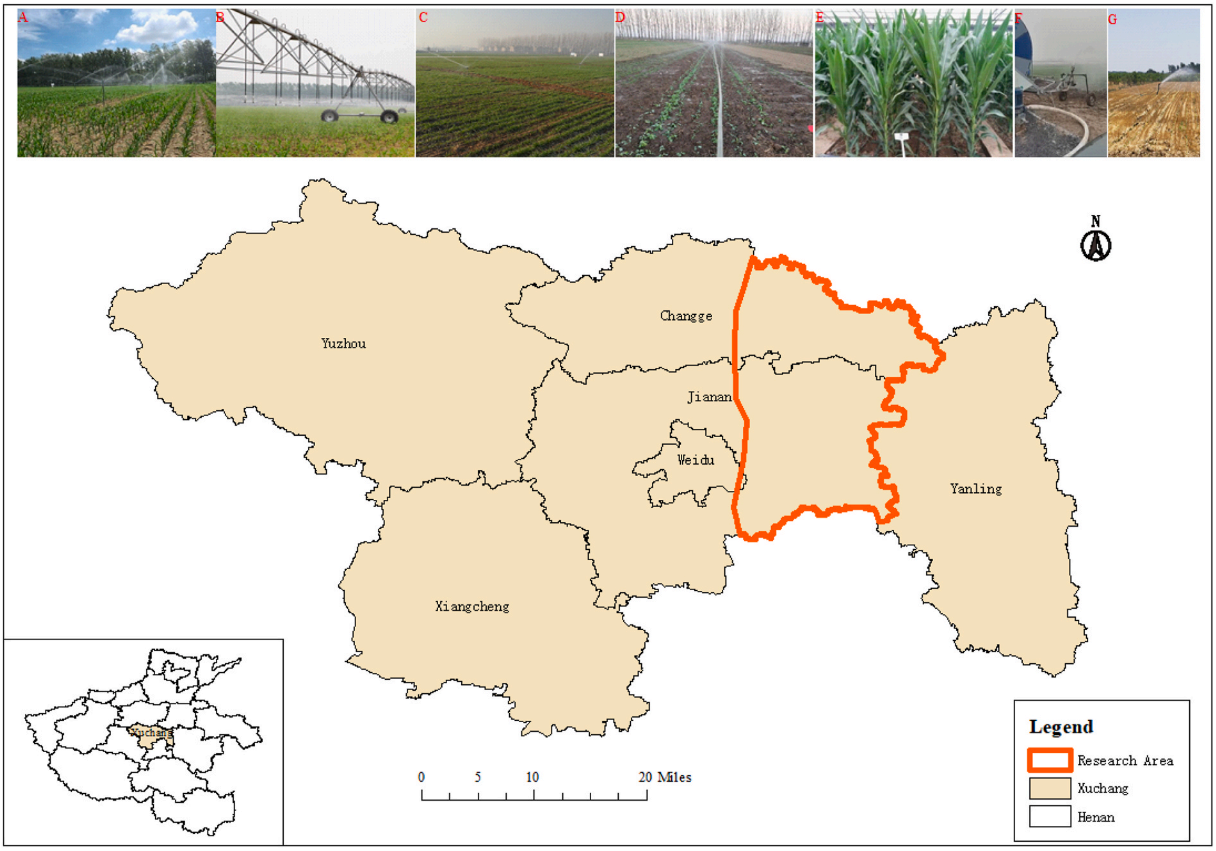

Fig. 1. Location of the study area in XCA and 7 types of irrigation mode. A-G in picture represent semi-fixed sprinkler irrigation, walking sprinkler systems, semi-automatic buried telescopic sprinkler irrigation, thin-soft spray tape irrigation, drip irrigation, self-driven winch sprinkler and manually moving spray gun irrigation, respectively.

2.2. Research methodology

2.2.1. Evaluation indicators and data sources

Seven distinct irrigation methods were chosen for optimization, each with its own unique characteristics. These methods included semi-fixed sprinkler irrigation, walking sprinkler systems, semi-automatic buried telescopic sprinkler irrigation, thin-soft spray tape irrigation, drip irrigation, self-driven winch sprinkler and manually moving spray gun irrigation. To distinguish between these seven irrigation modes, they were labeled as A, B, C, D, E, F, and G, respectively (Fig. 1 A-G). These modes are defined as follows.

A) The semi-fixed sprinkler irrigation involves a setup where the power machine, water pump, and main pipe remain in a fixed position throughout the entire irrigation season. However, the branch pipes, vertical pipes, and nozzles within the system can be disassembled, relocated, and reinstalled at various operating positions to facilitate rotating irrigation. **B)** The walking sprinkler operates by continuously moving in a parallel manner, evenly distributing water to the ground through a set of nozzles suspended from the equipment. **C)** The semi-automatic buried telescopic sprinkler irrigation involves a configuration where the pump and power machinery remain stationary. Trunk and branch pipes are buried underground, housing telescopic integrated sprinkler irrigation equipment within the branch pipes. These irrigation devices automatically emerge from the ground under the influence of water pressure and are manually retracted beneath the crop cultivation layer once the irrigation process is completed. **D)** The thin-soft spray tape irrigation operates by directing pressurized water to flow through small outlet holes on the soft spray tape, resulting in the formation of a fine drizzle, driven by the combined forces of gravity and air resistance. **F)** The self-driven winch sprinkler system involves the use of winch, which is mechanically driven to a rotate through a transmission mechanism. A PE pipe is wound this winch, and as the winch truck moves, the sprinkler head automatically sprays water. **G)** The manually moving spray gun irrigation consists of a branch pipe connected at one end to the water outlet and the other end to a spray gun. The spray head on the gun is adjusted to alter the spray direction under the influence of water pressure, resulting in water falling onto the field in the form of raindrops.

The optimization of water-saving irrigation technology was influenced by a multitude of factors, leading to the selection and innovation of irrigation evaluation criteria. There criteria were chosen and adapted with reference to both domestic and international literature, with a particular focus on the context of winter wheat-summer maize rotation [12,22,30]. The index system comprises three levels: one comprehensive-class index, five first-class indices, and 20 s-class indices (Table 1). Among these indices, data on engineering materials, annual maintenance costs, irrigation uniformity, and intensity, as well as irrigation water use efficiency, were collected through a three-year field experiment and observations of actual irrigation engineering construction and operation. Crop grain yield was determined through calculations considering the winter wheat-summer maize rotation, while irrigation water and power consumption were recorded using monitored equipment, with a comparison made to flood irrigation. Irrigation amount of A-G irrigation mode are 450, 375, 450, 750, 300, 300 and 375 m^3 per hectare in each time, respectively. Wheat and maize was irrigated four times totally in one crop rotation. To accurately collect objective research data pertaining to the irrigation systems, we distributed over 800 questionnaires in the study area across five counties: Jian'an, Changge, Yuzhou, Yanling, and Xiangxian. These questionnaires were administered to individuals involved in various aspects of the water sector, including members of farmers' water user associations, personnel at grassroots water management stations, professionals in engineering design and construction firms, as well as agricultural experts. The questionnaires were primarily centered on assessing social and ecological indicators. To quantify the responses, a specific comment set denoted as V = (good, better, moderate, poor, worse) was assigned corresponding values from the standard set U = (1, 0.8, 0.6, 0.4, 0.2). The mean membership degree was then considered as the quantification value for each indicator.

2.2.2. Indicator weight

The entropy method serves as an objective valuation method where indicator weights are established based on the information entropy derived from observed indicator values. This approach eliminates subjectivity in weight determination and enhances

Table 1
Comprehensive evaluation index system of water-saving irrigation model.

comprehensive-class index	Comprehensive evaluation index system				
first-class index	Economy	Technology	Society	Ecology	Resources
second-class index	Engineering materials Annual repair and maintenance cost Water and electricity cost Benefit-cost ratio	Irrigation uniformity Irrigation intensity Irrigation water utilization efficiency	Farmer popularity Crop adaptability Safety and reliability Difficulty of operation and management Difficulty of construction	Intelligent level Adaptation to fertigation Creation of farmland microclimate Adaptation to the mechanization	Water saving amount Irrigation water Consumption Energy saving Labor Saving
Source of index	acd	a	b	bc	ac

Note: The index data come from different sources, with a, b, c, and d in Table 1 representing field experiments, questionnaire surveys by experts and farmers, equipment monitoring and statistical yearbooks, and reference engineering documents, respectively.

differentiation among factors, preventing potential ambiguities in the analysis that may arise from minor difference in indicators. The ultimate goal is to comprehensively capture various types of information within the assessment [31,32].

(1) Data standardization

Profit indicators

$$a_{ij} = \frac{x_m - x_{min}}{x_{max} - x_{min}} \tag{1}$$

Cost indicators

$$a_{ij} = \frac{x_{max} - x_m}{x_{max} - x_{min}} \quad 1 \le i \le m \; 1 \le j \le k \tag{2}$$

where, i is the evaluation scheme, j is the evaluation indicator, x_{max} and x_{min} are the maximum and minimum values of the same evaluation indicator, m is the number of evaluation scheme, k is the number of evaluation indicator. Engineering materials, annual repair and maintenance cost, water-electricity cost, and crop water consumption are cost indicators, and the rest are profit indicators.

(2) Indicator information Entropy

Entropy value of the j-th indicator

$$e_j = -k \sum_{i=1}^{m} p_{ij} \bullet \ln p_{ij} \tag{3}$$

Among them,

$$k = {}^{1}/_{\ln m},\; p_{ij} = (1 + a_{ij}) \Big/ \sum_{i=1}^{m} (1 + a_{ij}) \tag{4}$$

(3) Entropy weight determination

Entropy weight of the j-th indicator

$$w_j = (1 - e_j) \Big/ \sum_{j=1}^{k} (1 - e_j) \tag{5}$$

The Analytic Hierarchy Process (AHP) is a systematic methodology used for hierarchically representing the components of various problems. Several scholars have actively contributed to the fuzzy extension of Saaty's priority theory [33,34]. This method is known for its conciseness and practicality, effectively integrating qualitative and quantitative aspects. Consequently, it has found widespread application in fields such as soil and water conservation, environmental research, and circular economy strategy development [35–37]. While the utilization of experience is valuable, it often introduces a high degree of subjectivity.

So, in this paper, the entropy method and AHP method were integrated to systematically determine indicator weights, striking a balance between data-driven objectivity and subjective expert input [38].

$$\alpha_j = \frac{w_j \times \beta_j}{\sum_{j=1}^{k} w_j \times \beta_j} \tag{6}$$

where, w_j and β_j represent the weight obtained with the entropy method and AHP method, respectively. α_j is the comprehensive weight.

2.2.3. The construction of water saving irrigation evaluation model

The TOPSIS method, which is closely related to the ideal scheme ranking method, involves constructing a weighted normalized decision matrix to calculate the distance between the evaluation scheme and the ideal or negative ideal solutions. The relative approach degree is used to establish the criteria for recognizing the quality of the objects under evaluation, with larger values indicating more ideal the solutions, and lower values signifying less favorable ones.

(1) Construct the normalized decision matrix R

$$R = [r_{ij}] \;,\; \left(r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} {x_{ij}}^2} \right) \tag{7}$$

Table 2
Benefit analysis of winter wheat-summer maize rotation under different irrigation modes.

Irrigation mode	Input cost (USD/hm^2)						Output benefits (USD/hm^2)			Net benefit analysis (USD/hm^2)
	Engineering materials (USD/hm^2)	Power cost (USD/hm^2)	Irrigation labor cost (USD/hm^2)	Field management (USD/hm^2)	Repair and maintenance cost (USD/hm^2)	Total input (USD/hm^2)	Winter wheat (kg/hm^2)	Summer maize (kg/hm^2)	Yield benefit from crop rotation (USD/hm^2)	
A	104.6c	36.5bc	89.7b	1534.5a	56.9b	1822.3b	1090.9b	1542.9b	6624.3b	4802.1 ab
B	119.6c	56.4a	89.7b	1534.5a	56.9b	1857.2b	1047.4c	1466.1bc	6321.3b	4464.1b
C	269.1b	41.7b	89.7b	1534.5a	56.9b	1991.9b	1220.5a	1647.9a	7212.7a	5220.8a
D	9.9e	52.1a	298.9a	1534.5a	1.2d	1896.6b	1168.9 ab	1633.2a	7047.2a	5150.5a
E	784.7a	20.8d	59.8c	1534.5a	77.1a	2477.0a	1260.4a	1693.4a	7427.1a	4950.0a
F	149.5c	37.6bc	59.8c	1534.5a	56.9b	1838.3b	1076.2bc	1352.5c	6104.3bc	4266.0b
G	18.7d	34.7c	89.7b	1534.5a	56.9b	1734.6bc	1098.6b	1251.1c	5902.5c	4167.9b
Coefficient of variation	129.21%	29.47%	75.69%	–	45.47%	12.70%	7.04%	10.89%	8.76%	8.96%
Median	119.6	37.6	89.7	–	56.9	1857.2	1098.6	1542.9	6624.3	4802.1
Extreme deviation	774.9	35.6	239.2	–	75.9	742.5	213.0	442.3	1524.5	1052.8

Note: The benefit analysis in this study referred to the winter wheat and summer maize cropping system. The engineering material inputs represented the costs invested from the water intake to the field, excluding the investment costs of water transmission pipelines and head hinge of motor-pumped well. Different letters within a column indicate significant differences among treatments within three seasons at 5% level by LSD test. Irrigation modes A-G represent the same meaning as above.

The standardization of data involved the assimilation and normalization of indicators, with cost-related indicators being transformed using the reciprocal method.

(2) Construct the weighted normalization matrix V

$$V = [v_{ij}] = R * W = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_k r_{1k} \\ w_1 r_{21} & w_2 r_{22} & \cdots & w_k r_{2k} \\ \vdots & \vdots & \cdots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_k r_{mk} \end{bmatrix} \tag{8}$$

$$W = \begin{bmatrix} w_1 & & & \\ & w_2 & & \\ & & \ddots & \\ & & & w_k \end{bmatrix}$$

where, W is the weight matrix of scheme indicators.

(3) Determine the ideal solution and negative ideal solution

$$< listaend > A^* = \max(v_{ij}) = [v_1^*\ ,\ v_2^*\ ,\ \cdots\ ,\ v_k^*] \tag{9}$$

$$A^- = \min(v_{ij}) = [v_1^-\ ,\ v_2^-\ ,\ \cdots\ ,\ v_k^-]\ \ 1 \le i \le m\ 1 \le j \le k \tag{10}$$

where, A^* and A^- are the ideal solution and negative ideal solution of the j-th indicator, respectively.

(4) Calculate the relative approach degree

$$S_i^* = \sqrt[2]{\sum_{j=1}^{k} (v_{ij} - v_j^*)^2} \quad S_i^- = \sqrt[2]{\sum_{j=1}^{k} (v_{ij} - v_j^-)^2} \tag{11}$$

$$C_i = \frac{S_i^-}{S_i^* + S_i^-} \tag{12}$$

where, S_i^*, S_i^- and C_i represent the distance to the ideal solution, the distance to the negative ideal solution and the relative approach degree, respectively. The larger the value of C_i, the more ideal the scheme is.

3. Results

3.1. Economic benefits analysis of major irrigation modes

The highest input was achieved in irrigation mode E, totaling $ 2477 USD/hm^2, surpassing that of irrigation mode G by a margin of 42.80% (Table 2). When considering the composition of engineering material costs, different irrigation systems exhibited significant variation, with a coefficient of variation (CV) value of 129.21%. Notably, in this regard, irrigation mode E was 79.5 times higher than that of irrigation mode D. Regarding power costs, irrigation mode B incurred the highest energy consumption, followed by mode D. In contrast to other irrigation modes, there was a substantial increase in labor costs due to the installation and relocation of the spray tape, which resulted in relatively lower irrigation water efficiency. Irrigation mode D stood out for its simplicity, user-friendliness, and minimal maintenance costs. In contrast, regular maintenance and management were essential for the sprinkler and drip irrigation modes (A, B, C, E, F, and G). In terms of yield output, substantial variations were observed in the winter wheat and summer maize rotation across different irrigation modes, with remarkable differences of 1425 kg/hm^2 and 2959 kg/hm^2, respectively. Irrigation mode E had the highest grain yield (2953.8 kg/hm^2), primarily owing to its consistent and synchronized application of sufficient water and fertilizer. In contrast, irrigation mode G, characterized by poor uniformity, was susceptible to human-related factors, leading to elevated labor costs and diminished yield benefits. From an economic standpoint, irrigation modes C and D emerged as the optimal choices for water-saving irrigation in the NCP, while modes F and G proved suitable for small-scale operations, gaining favor among farmers for their mobility and flexibility.

3.2. Comprehensive evaluation and results analysis

3.2.1. Data normalization

The statistical data (Table 3) for each scheme were collected through engineering information consultation, field crop experiments, extensive questionnaires, and equipment monitoring. The benefit-cost ratio of irrigation mode D was highest, standing at 3.716, which was higher than that of mode E by 23.95%. There were no significant differences among the other irrigation modes. Irrigation uniformity was consistently around 90% for modes A, B, and C. In contrast, modes E and G exhibited lower uniformity levels, ranging from

70% to 75%. Significant differences in irrigation intensity were observed among the micro-spray (D), drip (E), and sprinkler (A, B, and C). Specifically, mode D and G exhibited irrigation intensities were 3.1 times higher than the average of sprinkler modes (A, B, and C). Among these, irrigation modes A, C, and G were well-received by farmers. However, mode E, characterized by poor crop adaptability and high investment, found limited practical application in agricultural production.

Irrigation modes F and G were capable of creating a more favorable microclimate on the farm due to their larger sprinkler radius and higher head. Compared to flood irrigation, modes E and F conserved 3600 m^3/hm^2 irrigation water, whereas mode D exhibited the least water savings. In terms of energy consumption, the highest and lowest values were observed in irrigation modes B and E, respectively. Specifically, mode E was more energy-efficient than mode B, resulting in a 63.19% energy savings. However, irrigation mode D incurred the highest labor costs, increasing by 59.79 USD/ha with expanded application areas. In contrast, modes E and F demonstrated equivalent labor cost savings, similar to modes A, B, C, and G.

3.2.2. *Comprehensive weight determination of evaluation indexes*

The AHP method was adopted to calculate the subjective weight β. Objective weight W was obtained by the Entropy method (Eqs (1)–(5)). Comprehensive weight α was calculated by using Eq (6).

The results (Table 4) revealed that the top four objective weights (β) were as follows: labor-saving (0.128847), benefit-cost ratio (0.122354), irrigation water consumption (0.076437), and project material cost (0.074518), accounting for 40.22% of the total weights. When considering the objective weight perspective, irrigation intensity (0.142209) held the highest weight, followed by the uniformity coefficient (0.115216), energy savings (0.099509), and water and electricity costs (0.099504). These four key indices collectively represented 45.64% of the employing the Entropy weight method. Likewise, labor saving (0.185118), water and electricity costs (0.133305), uniformity coefficient (0.129319), and irrigation water consumption (0.109836) were combined to form the comprehensive weight, constituting a total weight of 55.76%.

3.2.3. *Comprehensive evaluation results based on the TOPSIS model*

Assimilation and normalization of indicators using Eq (7), and the weighted normalization matrix V was calculated with Eq (8).

$$V = \begin{bmatrix} 0.0088665 & 0.002009 & 0.047779 & \cdots & 0.041350 & 0.029103 & 0.069769 \\ 0.007758 & 0.002009 & 0.030872 & \cdots & 0.034459 & 0.014827 & 0.069769 \\ 0.003448 & 0.002009 & 0.041807 & \cdots & 0.041350 & 0.025379 & 0.069769 \\ 0.094039 & 0.096651 & 0.033446 & \cdots & 0.068917 & 0.017931 & -0.02791 \\ 0.001182 & 0.001483 & 0.083680 & \cdots & 0.027567 & 0.040287 & 0.083723 \\ 0.006206 & 0.002009 & 0.046356 & \cdots & 0.027567 & 0.028302 & 0.083723 \\ 0.049652 & 0.002009 & 0.050167 & \cdots & 0.034459 & 0.030344 & 0.069769 \end{bmatrix}$$

The ideal solution (A^*), negative ideal solution (A^-), the distance to the ideal solution (S^*), the distance to the negative ideal solution (S^-), and the relative approach degree (C) were determined with Eqs (9)–(12), respectively. The results were as follows.

Table 3
Statistical data of irrigation modes.

Indicator name	A	B	C	D	E	F	G
Engineering material/(USD/hm^2)	104.6cd	119.6c	269.1b	9.9e	784.7a	149.5c	18.7d
Annual repair and maintenance cost/(USD/hm^2)	56.9b	56.9b	56.9b	1.2c	77.1a	56.9b	56.9b
Water and electricity cost/(USD/hm^2)	36.5b	56.4a	41.7 ab	52.1a	20.8c	37.6b	34.7b
Benefit-cost ratio	3.63a	3.40a	3.62a	3.72a	2.99b	3.32 ab	3.40a
Irrigation uniformity/%	89.8a	91.6a	90.2a	85.0b	70.0c	88.4 ab	75.0bc
Irrigation intensity/(mm/h)	8.95c	9.30c	7.80c	27.00a	20.00 ab	12.70bc	19.90 ab
Irrigation water utilization efficiency	0.91b	0.89bc	0.92b	0.87c	0.94a	0.93a	0.94a
Farmers' popularity	0.89a	0.75b	0.96a	0.80 ab	0.45c	0.69b	0.90a
Crop adaptability	0.83b	0.85b	0.80bc	0.95a	0.51d	0.63cd	0.75c
Safety and reliability	0.90a	0.72b	0.80b	0.95a	0.69b	0.76bc	0.80b
Convenience of operation	0.95a	0.80b	0.92a	0.87 ab	0.49c	0.90a	0.85b
Difficulty of construction	0.85b	0.82b	0.75bc	0.95a	0.65c	0.95a	0.90a
Intelligence	0.60c	0.95a	0.82b	0.50c	0.90a	0.62c	0.55c
Adaptability to fertigation	0.80bc	0.89b	0.89b	0.75c	0.98a	0.80bc	0.75c
Creation of farmland microclimate	0.86b	0.87b	0.89 ab	0.72c	0.65c	0.95a	0.91a
Adaptation to mechanization	0.81b	0.87a	0.96a	0.90a	0.80b	0.829b	0.85 ab
Water saving/(m^3/hm^2)	3000b	3300a	3000b	1800c	3600a	3600a	3300b
Irrigation water consumption/(m^3/hm^2)	1800b	1500bc	1800b	3000a	1200c	1200c	1500bc
Energy saving/(kw h/hm^2)	562.6b	286.6c	490.6bc	346.6c	778.9a	547.2b	586.6b
Labor cost saving/(USD/hm^2)	149.5b	149.5b	149.5b	−59.8c	179.4a	179.4a	149.5b

Note: Different letters within a row indicate significant differences among treatments within three years at 5% level. Irrigation modes A-G represent the same meaning as above.

Table 4
Values of weight factors, ideal and negative ideal.

Indicators	β	W	α	A*	A⁻
Engineering material	0.074519	0.086201	0.107235	0.094039199	0.001182
Annual repair and maintenance cost	0.060617	0.095624	0.096767	0.096651389	0.001483
Water and electricity cost	0.080249	0.099504	0.133305	0.083679518	0.030872
Benefit-cost ratio	0.122354	0.009883	0.020188	0.008218014	0.006631
Irrigation uniformity	0.067234	0.115216	0.129319	0.052893418	0.04042
Irrigation intensity	0.020365	0.142209	0.048348	0.029840746	0.00862
Irrigation water utilization efficiency	0.03699	0.000242	0.000149	0.000059	0.000054
Farmers' popularity	0.070082	0.018728	0.021911	0.010008	0.004691
Crop adaptability	0.046127	0.018728	0.021911	0.004911	0.002636
Safety and reliability	0.013714	0.005155	0.00118	0.000524	0.000381
Convenience of operation	0.027456	0.014665	0.006721	0.002881	0.001486
Difficulty of construction	0.019456	0.006966	0.002262	0.000961	0.000658
Intelligence	0.035579	0.021424	0.012725	0.006300	0.003315
Adaptability to fertigation	0.023035	0.00415	0.00159	0.000703	0.000538
Creation of farmland microclimate	0.010254	0.006895	0.00118	0.000503	0.000344
Adaptation to mechanization	0.016219	0.001693	0.000458	0.000192	0.000160
Water saving	0.026308	0.0860754	0.037000	0.022531	0.011265
Irrigation water consumption	0.076437	0.086075	0.109836	0.068900	0.027567
Energy saving	0.076437	0.099509	0.073000	0.040286	0.014827
Labor cost saving	0.128847	0.086062	0.185118	0.083723	−0.027907

Table 5
Evaluation results for the main irrigation modes.

Irrigation modes	Semi-fixed sprinkler irrigation (A)	Walking sprinkler (B)	Semi-automatic buried telescopic sprinkler irrigation (C)	Thin-soft spray tape irrigation (D)	Drip irrigation (E)	Self-driven winch sprinkler (F)	Manually moving spray gun irrigation (G)
S*	0.138	0.147	0.144	0.125	0.141	0.143	0.117
S⁻Score	0.102	0.099	0.101	0.142	0.127	0.114	0.113
	0.425	0.402	0.412	0.532	0.474	0.445	0.490
Sort	5	7	6	1	3	4	2

3.3. Principal component analysis of different irrigation modes

The seven irrigation modes were evaluated with principal component analysis to delve deeper into the similarities and underlying connections among irrigation patterns (Fig. 2). Cumulatively, the first two principal components PC1 and PC2 accounted for 76.3% of the raw data information, matching the statistical significance. In the score plot (a), it's evident that irrigation modes B and C exhibited strong similarity. mode G was positioned close to the center of mass point. Irrigation modes A, B, C, G, and F were clustered within the 95% confidence interval, indicating significant similarities among them. Conversely, mode D (E) stood apart from the other irrigation modes, indicating substantial differences compared to other irrigation modes.

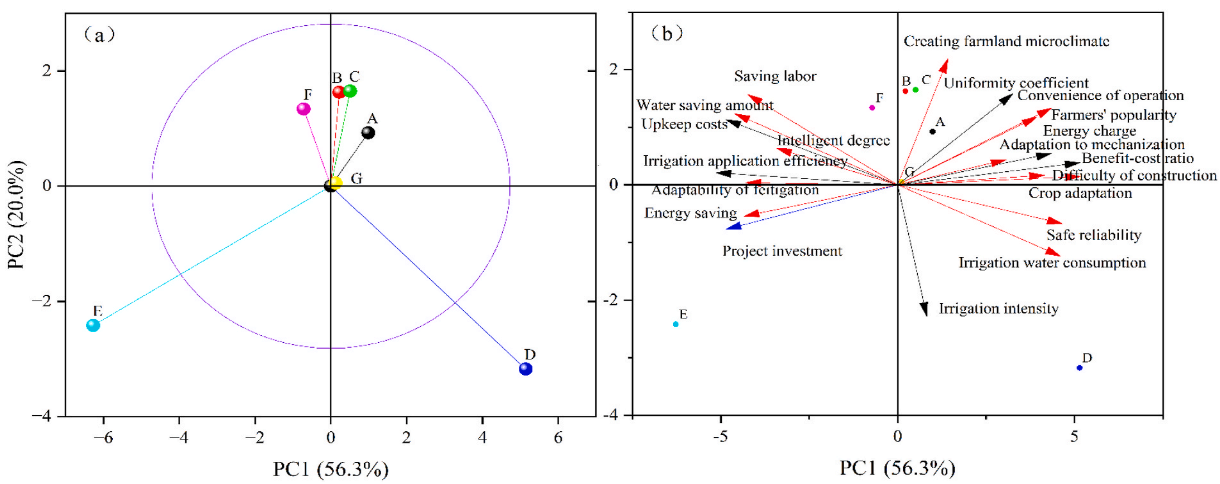

Fig. 2. Principal component analysis of the seven irrigation modes, a and b represent the score plot and the loading plot, respectively.

The loading plot (b) implied that PC1 mainly represented social evaluation indicators. It revealed significant positive correlations among indicators that contribute substantially to PC1, such as irrigation uniformity, convenience of operation, farmers popularity, energy efficiency, construction complexity, crop adaptability, safety and reliability and irrigation water consumption. On the contrary, economic evaluation indicators containing labor saving, water saving, maintenance costs, fertigation adaptability, energy efficiency and project investment displayed negative correlations with PC1. Farmland microclimate made great contribution to principal component PC2 which mainly represented ecological evaluation indicators, negative correlation was also obtained between irrigation intensity and PC2.

3.4. Irrigation technology application in the experimental area

The manually moving spray gun irrigation was the dominant method, covering 94.07% of the surveyed study area (Table 6). The thin-soft spray tape irrigation accounted for 3.68% of the area, while other irrigation methods were applied in smaller areas, ranging from 66.67 to 200 ha. The benefit analysis in Table 4 indicated that the thin-soft spray tape irrigation and manually moving spray gun irrigation occupied the top two positions, aligning with the irrigation technologies used in practical agricultural production. Notably, the thin-soft spray tape irrigation was particularly well-suited for farmers with smaller irrigated areas (irrigated area <1 ha). As the irrigated area continued to increase, the manually moving spray gun irrigation emerged as the preferred choice. Drip irrigation secured the third position in the ranking, but it saw limited use in crop cultivation practices. Instead, it was predominantly employed for cash crops such as peppers and vegetables by smallholder farmers. In the case of irrigation mode C, it possessed the unique capability to automatically emerge from the ground under the influence of irrigation water pressure. This innovation effectively addressed the longstanding issue associated with traditional fixed sprinkler irrigation, which often hindered crop harvesting and field cultivation. The government actively demonstrated and promoted the use of waking sprinkler (B) in contiguous cultivation lands, effectively raising awareness about water conservation among the populance. The application areas for self-driven winch sprinkler (F) and semi-fixed sprinkler irrigation (A) were comparatively limited. The former was mainly utilized by professional cooperatives as a temporary drought resistance equipment, while the latter found application in family farms and field irrigation experiments. Horizontally, significant differences in the arrangement of irrigation modes were observed across different townships. In Shixiang, all seven irrigation modes were utilized, whereas only moving spray gun irrigation was employed in Dazhou and Zhangpan. This observation underscores the importance of taking into account the preferences of local farmers and the specific conditions of each area when determining the optimal irrigation methods.

3.5. Probability of different agricultural businesses choosing irrigation technology

A questionnaire survey encompassing a range of agricultural entities, including small-scale farmers, large and specialized family businesses, family farms, farmer cooperatives, and agribusinesses, was applied to assess the probability of employing different irrigation technologies. Fig. 3 illustrates the relationships between different agricultural businesses and their choices of irrigation technology through a Sankey diagram. Following statistical analysis, the self-driven winch sprinkler, manually moving spray gun irrigation and thin-soft spray tape irrigation received scores of 0.9, 0.9, and 0.82, respectively. The line widths on the map revealed that irrigation modes D, G, and A were predominantly favored by small farmers, large and specialized family business, and small farmers. Likewise, modes C, F, E, and B were popular choices among family farmers, family farmers, agribusinesses, and farmer cooperatives. The probability of selecting semi-fixed sprinkler irrigation and walking sprinkler was lower when compared to other irrigation modes. Notably, the latter was predominantly favored by agribusinesses and farmer cooperatives exclusively. Farmer cooperatives and agribusinesses exhibited a tendency to diversity their irrigation choices, which encompassed irrigation modes C, F, E, and B. This diversification was driven by their financial resources and advantages in funding. Furthermore, the thin-soft spray tape irrigation was

Table 6
Irrigation mode area statistics in the surveyed areas (ha).

Countryside	Manually moving spray gun irrigation (G)	Thin-soft spray tape irrigation (D)	Walking sprinkler (B)	Drip irrigation (E)	Self-driven winch sprinkler (F)	Semi-fixed sprinkler irrigation (A)	Semi-automatic buried telescopic sprinkler irrigation (C)
Shi xiang	2533.33	400.00	66.67	33.33	33.33	33.33	33.33
Nan xi	3960.00	386.67	0.00	33.33	0.00	0.00	33.33
Gu qiao	3080.00	393.33	33.33	0.00	33.33	0.00	33.33
Dong cun	3273.33	66.67	33.33	0.00	0.00	33.33	33.33
Da zhou	1626.67	0.00	0.00	0.00	0.00	0.00	0.00
Xiao zhao	2186.67	0.00	0.00	0.00	0.00	0.00	33.33
Chen cao	5626.67	66.67	66.67	0.00	33.33	0.00	33.33
Wu nv dian	4673.33	0.00	0.00	66.67	0.00	0.00	33.33
Deng zhuang	973.33	0.00	0.00	33.33	0.00	0.00	0.00
Zhang pan	4006.67	0.00	0.00	0.00	0.00	0.00	0.00
Jiang guan chi	1613.33	0.00	0.00	0.00	0.00	0.00	33.33
Total	33553.33	1313.33	200.00	166.67	100.00	66.67	266.67

highly popular in the majority of small-peasant economy areas, comprising 44% of the selection. In parallel, large and specialized family business accounted for more than 36% of the preference for irrigation mode G, while family farms, farmer cooperatives, and agribusinesses contributed 28%, 22 %, and 32%, respectively to modes F, B, and E.

4. Discussion

4.1. Irrigation technology optimization method

The statistical communique indicated that the yield per unit area of winter wheat increased by 4.79% from 2010 (7049 kg/hm^2) to 2020 (7386 kg/hm^2), and the yield of summer maize rose from 6449 kg/hm^2 to 7206 kg/hm^2, with a growth rate of 11.7%. Comparing these yields in Table 2, there was still substantial space for increasing crop productivity. Therefore, the adoption of irrigation modifications became crucial in order to attain the maximum possible increase in yield. To achieve this, appropriate optimization method for evaluating irrigation performance were employed. While indicators based on direct measurements enable a swift and straightforward problem assessment, they come with drawbacks, including high subjectivity, data collection uncertainties, and a considerable time investment ([39] Dejen and Z.A, 2015; [40]). A fuzzy-based methodology, built upon the well-established multi-criteria decision method known as the Analytical Hierarchy Process (AHP), was proposed for assessing irrigation projects [13]. This approach considered major criteria encompassing technical, managerial, environmental, social, and economic aspects. While this methodology offers programmability and the capability to address complex issues, it comes with the disadvantage of requiring technological expertise and being inherently subjective [22]. Another study, conducted by Zwart and Leclert [41], employed remote sensing techniques to evaluate irrigation performance in Mali. This remote sensing method demonstrated the ability to cover extensive geographic areas and proved valuable in data-scarce regions. Nevertheless, it is important to acknowledge its limitations, such as the high cost associated with obtaining high-resolution data and its susceptibility to interference from cloud cover [12]. In conclusion, each optimization method has its own set of advantages and limitations. In terms of determining the weights of the index system, subjective evaluation methods like expert survey, AHP, comparative weighting, and fuzzy statistics were relatively straightforward and practical. However, they can introduce a high significant degree of bias into the assessment process.

Objective evaluation methods, such as principal component analysis, entropy weight, the critic method, and the mean square difference method, are known for their high accuracy and informativeness, but these methods tend to provide less explanatory insight. In our research, we employed an integrated weighting approach inspired by Liu et al. [29]. This approach effectively blends the AHP with Entropy theory, ensuring the reliability of our evaluation results by accommodating both subjective and objective factors.

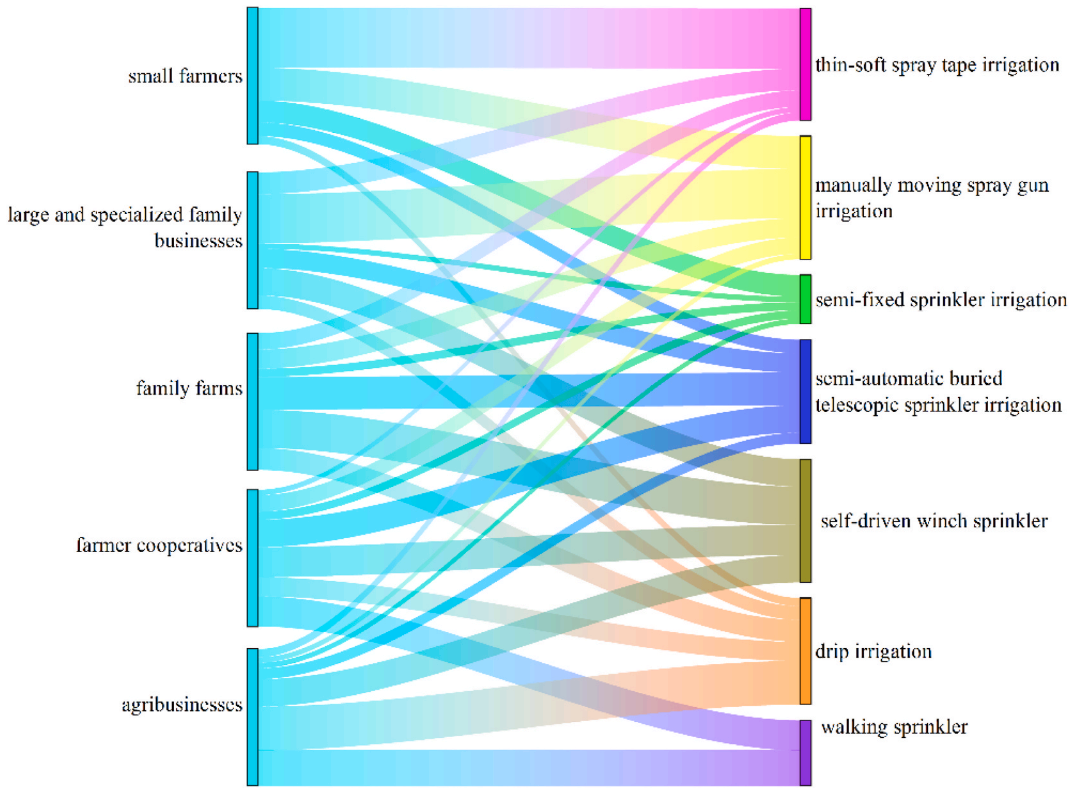

Fig. 3. Sankey diagram analysis between agricultural businesses and irrigation technology.

Furthermore, we maximized the utility of the original statistical indicator data by implementing the TOPSIS method. Principal component analysis revealed significant differences between irrigation mode D and E. In the case of thin-soft spray tape irrigation (D), it entailed lower initial investment but required more labor in the field. Conversely, irrigation mode E involved higher initial investment but offered labor-saving benefits. Mode G was positioned closed to the center of the mass point, with its associated indicators falling within an intermediate range, lacking clear advantages or disadvantages. The results of principal component analysis further validated the accuracy and soundness of the comprehensive evaluation model (Fig. 2 and Table 5).

In irrigation districts, the most crucial factors influencing agricultural water management were identified as the weights of the engineering and management indices, ranking as the top two priorities. Additionally, there was a notable emphasis on factors such as irrigation insurance probability, optimal irrigation scheduling, and critical water irrigation [22]. Zhong et al. [42] emphasized that training farmers, improvement of cropping patterns, land levelling, and modernization of the irrigation systems were high-ranked strategies to prioritize agricultural water demand management. In contrast to the regulation of weight indexes in previous studies, this study assigned the highest importance to four key indicators: labor saving, water and electricity costs, irrigation uniformity, and irrigation water consumption, accounting for 55.76% of the total weight. This difference can be attributed to variations in the classification and prioritization of indexes. Labor saving and water-electricity costs, irrigation uniformity, and irrigation water amount represented the economic, technical, and resource-related indexes, respectively. This suggested that the economic benefits, irrigation quality, and water-saving effects were the main considerations to the irrigation mode optimization. This conclusion was in line with the optimized results of irrigation mode (Table 5). The TOPSIS method and the integrative weighting theory of "AHP + Entropy", as proposed in this paper, offer a comprehensive approach that considers both subjective and objective factors. These methods can serve as a solid scientific foundation for water resources management and the evaluation of irrigation technology.

4.2. Characteristic analysis of irrigation patterns based on indicators

The implementation of micro-sprinkling irrigation has proven to be effective in increasing grain yield while simultaneously reducing the overall volume of irrigation water used. This underscores the importance of offering water-saving technological support to smallholders engaged in winter wheat production on the NCP [43]. Water productivity can be improved by adopting appropriate irrigation technologies, thereby achieving increased yields with reduced water consumption. Sprinkling irrigation, micro-irrigation, drip irrigation under plastic film mulch, and subsurface irrigation have experienced rapid and widespread adoption [44]. The evaluation scores (Table 5) showed that the thin-soft spray tape irrigation and manually moving spray gun irrigation achieved a "good" rating. These irrigation methods are mainly characterized by their low investment requirements, ease of operation, space and time constraints, low failure rates, and high adaptability. They are considered the predominant irrigation modes for smallholders in wheat-maize cropping systems. Drip irrigation (E) is a highly efficient irrigation technique. Increasing the frequency of irrigation with drip irrigation systems helps maintain higher soil water content in the top soil layers, resulting in improve crop water utilization and yield [9,45]. In this study, drip irrigation secured the third position in rankings (Table 5), demonstrating its significant water-saving potential. However, the adoption of drip irrigation remains limited in well-irrigated areas of south central NCP, this can be attributed to substantial vast investment (Table 2) required per hectare and the unpredictable spatiotemporal rainfall that can render irrigation facilities being not utilized.

Self-driven winch sprinkler (F) and semi-fixed sprinkler irrigation (A) both fall into the "general" category. Compared to the complex operation and inconvenient maintenance associated with fixed sprayers [46], irrigation mode F stands out for its simplicity and flexibility. This makes it particularly well-suited for large-scale wheat and soybean cultivation, making it the preferred as an efficient irrigation equipment. The field survey indicated that an efficient irrigation coverage of 1.33 ha can be achieved within a single day. However, a significant drawback lies in the increased electricity consumption due to the installation of a booster pump to elevate water transportation pressure. Additionally, the movement of the winch is restricted by the tall corn stalks, highlighting a noteworthy issue that warrants attention and improvement. The optimization of irrigation modes involves striking a balance between maximizing rainfall use efficiency, minimizing labor requirements, and maximizing crop yield [47]. Small-scale farmers often resort to using semi-fixed sprinkler systems, despite the higher labor costs associated with mobile facility installation.

The advances in overhead sprinkler systems and other technologies are empowering farmers with greater control over their water usage [48]. In our research, the walking sprinkler (B) and semi-automatic buried telescopic (C) are at the "low" level (Table 5). Irrigation mode B is characterized by uniformity spraying, high level of mechanization and automation, and labor-saving features, making it particularly suitable for large-scale land layouts. However, it's important to note that the power consumption associated with this mode is 1.08–2.71 times higher than that of other irrigation modes (Table 2). The utilization of low-cost sensor in the automated irrigation system resulted in reduced power consumption, ultimately contributing to a reduction in water wastage [49]. Irrigation facility of mode C, which is buried underground at depths exceeding 50 cm, has gained popularity in recent years without causing disruptions to crop harvesting and field cultivation. However, it comes with a substantial investment cost, which is 27 times higher than that of thin-soft spray tape irrigation. Additionally, it can be challenging to maintain if not properly managed.

4.3. Response of new types of agricultural businesses to irrigation technology

As society evolves and urbanization levels increase, the agricultural business landscape and its structure are undergoing transformation. Participatory irrigation management has emerged as a key strategy, offering farmers significant incentives to enhance and sustain management efficiency while also fostering the adoption of innovative water-saving irrigation technologies [50]. In China, the agricultural business is categorized into five distinct types: small farmers, large and specialized family businesses, family farms, farmer cooperatives, and agribusinesses. These categories exhibit significant disparities in terms of scale and modernization level within the agricultural sector. Gong et al. [51] pointed out the importance of ongoing efforts by public authorities to improve the efficiency of land allocation, promote large-scale agricultural operations, nurture emerging agricultural entities, and elevate the degree of specialization in agricultural production.

The Sankey diagram indicated that the distribution of contributions from various sectors to different modes, highlighting that large and specialized family business account for 36% of irrigation mode G, small farmers contribute 44% to irrigation mode D, family farms make up 28% of irrigation mode F, farmer cooperatives represent 22% of irrigation mode B, and agribusinesses play a significant role in irrigation mode E, contributing 32% (Fig. 3). Based on our analysis of irrigation technology application and considering the current irrigation development levels in south central NCP (Fig. 1), we have formulated some practical recommendations. For instance, small farmers are characterized by their self-sufficient planting practices. Furthermore, it is crucial to recognize that subsistence economies, particularly those with small-scale farming operations, are more susceptible to the adverse effects of droughts [52]. This heightened vulnerability underscores the need for targeted interventions to mitigate the impact of droughts on such communities. Therefore, the thin-soft spray tape irrigation (D) was recommended by economical and applicable properties. Large and specialized family businesses exhibit a reluctance to make substantial long-term investments in land and hire additional labor. Instead, they have opted for strategies such as cultivating cash crops an improving their multiple-crop index to boost output. To achieve this, they have embraced relevant irrigation technologies, specifically semi-fixed sprinkler irrigation (A) and manually moving spray gun irrigation (G) (Table 6). These technologies are being used in conjunction with the cultivation of cash crops like chili peppers, garlic, and peanuts. Family farms are distinguished by their specialization, integration, systematization, and socialization, which depend on the local natural resource conditions and enthusiastically embrace new techniques and equipment to cultivate high-value-added agricultural products [53]. In the initial stage of their operations, the majority of managers tend to augment their investments in acquiring irrigation facilities and improving the quality of their farmland. Consequently, we recommend the adoption of semi-automatic buried telescopic sprinkler irrigation (C), self-driven winch sprinkler (F) and drip irrigation (E) as suitable options for these managers (Fig. 1). Agricultural co-operatives are frequently recognized as an effective means of bridging the divide between smallholders and modern agriculture [42]. Farmer cooperatives have the potential to establish market connection for smallholder and large and specialized family businesses to strengthen farmers' organizations and intensifying agricultural practices. So, walking sprinkler (B) and large winch irrigation (F) were recommend to support crop irrigation. Agricultural industrial organizations play a pivotal role in motivating smallholders, facilitating resource integration, and improving the resilience and risk tolerance of small-scale farmers [54,55]. In reality, agribusinesses primarily establish a vested interest through contracts and orders, even though they may not be directly involved the actual crop cultivation process. Nevertheless, these agribusinesses can offer irrigation technical guidance and financial assistance to the four aforementioned emerging types of agricultural enterprises.

Unfortunately, the selected evaluation indicators are not sufficiently comprehensive when constructing the optimization model. As a result, the research outcomes primarily serve as guidance for the application of irrigation technology in well-irrigated areas. To provide specific irrigation mode recommendations to different agricultural business, it is essential to design experiments for verification, rather than solely relying on anecdotal experience. Looking ahead, the most promising direction for the future appears to be irrigation modes that incorporate integrated intelligent technology, incorporating both hardware and software elements, facilitated by remote control, communication methods, image recognition, and visible light spectrum information.

5. Conclusion

Determining the appropriate irrigation technology holds immense significance for the well-irrigated areas of the North China Plain. This paper focused on 7 common irrigation modes and 20 key indicators spanning economic, technological, social, agro-ecological, and resource aspects for evaluating the adoption of irrigation technology with a method integrated "AHP + Entropy". The results underscored that economic benefits, irrigation quality and water-saving efficiency were the primary factors influencing irrigation mode optimization. Semi-automatic buried telescopic sprinkler and drip irrigation required substantial investments, while walking sprinkler exhibited high electricity consumption. Self-driven winch sprinkler demonstrated limitations in crop adaptability. Thin-soft spray tape irrigation and manually moving spray gun irrigation were noted for their simplicity. The sequence of scores ranked as follows: thin-soft spray tape irrigation > manually moving spray gun irrigation > drip irrigation > self-driven winch sprinkler > semi-fixed sprinkler irrigation > semi-automatic buried telescopic sprinkler irrigation > walking sprinkler. Thin-soft spray tape irrigation, manually moving spray gun irrigation, self-driven winch sprinkler and walking sprinkler were recommended for small farmers, large and specialized family businesses, family farms, and farmer cooperatives, respectively. Agribusinesses were encouraged to provide irrigation technical advice and financial support. The research provide valuable scientific support and recommendations for the practical application of irrigation technology in agricultural production.

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Data availability

The data that has been used is confidential.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Yushun Zhang: Writing – original draft, Supervision, Conceptualization, Methodology, Software. **Jian Liu:** Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization, Visualization. **Xinqiang Qiu:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Conceptualization. **Wenfeng Li:** Visualization, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Haochen Yang:** Validation, Supervision, Resources, Project administration, Investigation, Visualization. **Haixia Qin:** Investigation, Formal analysis, Data curation, Conceptualization, Methodology, Supervision. **Yanping Wang:** Visualization, Software, Resources, Project administration, Investigation. **Min Wang:** Supervision, Software, Resources, Investigation, Conceptualization. **Hengkang Zhu:** Visualization, Validation, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Xinqiang Qiu reports financial support was provided by Henan Provincial Department of Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The optimization results for the primary irrigation modes at well-irrigated areas of the NCP are presented in Table 5. The top three irrigation modes were D, G, and E, scoring 0.532, 0.490, and 0.474, respectively. Conversely, the walking sprinkler (B) was deemed unsuitable for smallholder conditions and ranked lowest. These results aligned with the real-world circumstances.

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