Journal of Arid Environments 231 (2025) 105458

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Determining the best strategies to improve agricultural water productivity in arid and semi-arid regions: An ordinal priority approach

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ARTICLE INFO

Keywords:
Operational effectiveness
Mashhad
Institutional and policy interventions
OPA

ABSTRACT

The exponential growth of the world's population has significantly increased the demand for food. Agriculture, as the main provider of food, faces severe constraints due to limited water resources. In this context, improving agricultural water productivity is one of the most effective solutions to address water crises, ultimately leading to increases in both the quantity and quality of agricultural products. This study aimed to identify and prioritize the most effective strategies for improving agricultural water productivity in arid and semi-arid regions, with a particular focus on Mashhad County in Iran. Through interviews with experts and the use of the Ordinal Priority Approach (OPA), four criteria (operational effectiveness, social acceptance, economic efficiency, and ecological sustainability) and 27 strategies were identified and prioritized. The results revealed that institutional and policy interventions received the highest priority, followed by capacity-building and awareness interventions, and irrigation technology interventions. Agronomic and genetic interventions, as well as water resource management interventions, received the lowest priority. The findings and recommendations of this study provide valuable insights for policymakers, water managers, and agricultural stakeholders to develop and implement effective strategies to improve water productivity, enhance food security, and promote sustainable agricultural practices in arid and semi-arid regions.

1. Introduction

Global population growth has accelerated rapidly in recent decades, reaching 8 billion in November 2022 and projected to exceed 9 billion by 2037, driven largely by demographic expansion in Asia and Africa (Meena et al., 2023). This surge in population, combined with rising living standards and industrial development, has sharply increased demand for both food and freshwater resources (Ali and Talukder, 2008; Du Plessis and du Plessis, 2019). Agriculture already accounts for approximately 70 % of global freshwater withdrawals, underscoring the sector's critical dependence on reliable water supplies.

At the same time, climate change-induced shifts in precipitation patterns and more frequent drought events are reducing water availability in many key production areas (Meena et al., 2023; Zargan and Waez-Mousavi, 2016). Concurrently, urban and industrial water demands are expected to rise by up to 80 % by 2050, intensifying competition for finite freshwater resources among agriculture, cities, and ecosystems (Endo et al., 2017; Flörke et al., 2018; Covino et al., 2013). Without effective management, these pressures threaten to constrain agricultural output and compromise global food security.

In Iran, despite significant challenges to food production, such as rapid population growth and the increasing demand for both quantity and quality of food, especially in urban areas, there are parallel concerns regarding climate change. More specifically, the forecasted worsening of the water crisis in both quantity and quality presents a significant challenge to ensuring sustainable food production and water resource management. As the government aims to balance food security with the nation's water resources, the environmental impact of agriculture must also be minimized. Numerous measures are being implemented to tackle water scarcity and boost food production, but agricultural experts argue that the core issue is not merely the lack of water, but the inefficient management of water resources and the insufficient development of

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https://doi.org/10.1016/j.jaridenv.2025.105458
Received 15 February 2025; Received in revised form 5 August 2025; Accepted 5 August 2025
Available online 15 August 2025

Table 1
Literature on agricultural water productivity.

Authors	The purpose of the research	Methodology	Result
Abera et al. (2025)	Modeling maize production and water productivity under deficit irrigation and mulching as sustainable agricultural water management strategies	AquaCrop model	The AquaCrop model effectively simulates maize yield and water productivity under deficit irrigation with mulch, indicating its potential in improving sustainable agriculture in semi-arid areas.
Ma et al. (2025)	Enhancing maize yield and water productivity through root-shoot coordination under mild water stress	Field trial over two years (2020–2021) with two planting densities (70,000 plants/ha and 90,000 plants/ha) and three water deficit treatments (full irrigation, mild, and moderate water stress)	Dense planting (90,000 plants/ha) increased leaf area index (LAI), root development in topsoil, and water use efficiency (WUE). Mild water deficit treatment enhanced root development in deeper soil layers, leading to improved water utilization and yield.
Kingra and Kukal (2024)	Address the impact of climate change on agricultural water productivity in Indo-Gangetic Plains	Review of climate change effects on agriculture, water management strategies, and practices	Emphasizes the role of climate-smart agriculture, including rainwater harvesting, irrigation techniques, and policy measures, to improve water-use efficiency and secure water for future agricultural needs.
de Jong et al. (2021)	Improve agricultural water productivity with a focus on rural transformation	Literature review and policy analysis	Focuses on the need for comprehensive rural transformation to enhance water productivity. Highlights that irrigation is the largest water user and improvement in water productivity requires significant changes in agricultural systems and farmer support.
Patra et al. (2022)	Explore the prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit conditions	Review of the role of hydrogels in improving water retention, irrigation efficiency, and crop productivity	Highlights the potential of hydrogels to act as water retention agents, improving soil moisture, reducing irrigation frequency, enhancing nutrient uptake, and supporting crop growth under drought conditions. Emphasizes their ability to increase yield, water use efficiency, and soil health in arid and semi-arid regions.
Larraz et al. (2024)	Develop socio-economic indicators for water management in the South-West Europe territory, focusing on water productivity and employment intensity	A set of 11 socio-economic indicators to evaluate the economic and social impacts of water use across economic sectors in SUDOE	Highlights the need to integrate both economic and social dimensions in water management. The results show that water productivity is higher in the tertiary sector than in the primary and secondary sectors, with the north of SUDOE exhibiting the highest productivity. It emphasizes the importance of focusing on efficient water allocation, considering both environmental and social impacts, particularly in areas facing high water stress. The study also discusses potential changes in agricultural and livestock practices in water-scarce areas.
Drastig et al. (2023)	Review the concept of Nutritional Water Productivity (NWP) in agriculture, its promotion, and how it is assessed.	A systematic literature review of 40 studies on NWP, analyzing methodologies, tools, and the relationship between water use and nutritional value produced in agriculture.	Highlights the variability in methodologies and the need for standardized metrics for NWP. It concludes that while NWP can optimize the use of limited water resources for more nutritious food, its application is limited by data and methodological inconsistencies. It recommends a combined approach integrating NWP with water scarcity impact (WSI) to better address both water efficiency and food security, with a focus on improving data collection and modeling tools for reliable assessments.
Zamani et al. (2021)	Investigating the impact of water-pricing policies on water productivity	Positive Mathematical Programming (PMP) model	Water-pricing policy can alter cropping patterns and irrigation systems within a region and serve as an incentive to encourage farmers to adopt more modern and efficient irrigation systems.
Ozcelik et al. (2021)	To critically evaluate the appropriateness of water productivity as an indicator for assessing water efficiency management in agriculture.	Application of Logarithmic Mean Divisia Index (LMDI) decomposition analysis to examine changes in agricultural water productivity across 34 countries, using data from 1995 to 2010.	The results reveal a weak relationship between changes in water productivity and water efficiency. Changes in water productivity are primarily driven by labor productivity and capital intensity rather than water efficiency. It is concluded that water productivity should not be used to assess efficient water management strategies, and independent indicators such as biomass per volume of water should be used instead.
Huang et al. (2021)	Investigation of the impact of conservation tillage on the productivity of corn and soybeans and their water use.	improved process-based agroecosystem model (DLEM-Ag)	Conservation tillage should be complemented with water and nutrient management practices to enhance soil water retention and optimize nutrient use in agricultural lands in the region.
Eid and Negm (2019)	Improving agricultural product performance and water productivity through productivity and sustainable techniques	experiment	Examples of engineering techniques that have led to improved water productivity include: (1) laser land leveling, (2) development of new drip irrigation systems, and (3) pulse irrigation.

(*continued on next page*)

Table 1 (*continued*)

Authors	The purpose of the research	Methodology	Result
Farooq et al. (2019)	The role of physiological and agronomic considerations in improving water use productivity in crop plants	Review	modified planting times, seeding rates, planting geometries, utilizing high-efficiency irrigation systems, better soil fertility management, mulching to reduce soil evaporation, and weed management enhance agricultural water productivity on the farm.
Shakoori and Morsali (2018)	The relationship between climatic and environmental factors and the water productivity of rural communities.	Questionnaire and interview	Climatic and environmental changes play an important role in improving the water productivity of rural communities in our country.
Morsali et al. (2017)	Identification and prioritization of the most important processes for improving water productivity	library studies and field activities	The major reasons for the low agricultural water productivity at the national level are related to agricultural production processes such as the lack of a defined cropping pattern for each region, the way water is consumed like the lack of water recycling, and the high level of agricultural product losses.
Karimi and Jolaini (2017)	Analysis of irrigation productivity in key agricultural crops	Interviews with experts and farmers	It is suggested that crops with high water use and lower economic yield, such as alfalfa, be removed from the cropping pattern. This will both reduce water use and abstraction, and also ensure higher economic returns for farmers.
Kohansal et al. (2013)	Assessment of water productivity for agricultural products	Analytical	Crops with high water use and low economic returns (such as barley and sugar beets) should be replaced with crops that reduce water extraction and increase economic profits for farmers (such as rapeseed and wheat).
Keshavarz and Dehghanisanije (2012)	Analyzing water productivity y indicators and solutions for enhancing agricultural water productivity.	Review	The utilization of modern irrigation methods such as rain-fed and drip irrigation, coupled with improved irrigation management on the farm, has typically increased water productivity.
Ali and Talukder (2008)	Investigating factors affecting water productivity	library	The combination of biological water-saving techniques with engineering, agricultural, and soil manipulation solutions can increase water use productivity.

technologies for optimal water use (Haghayeghi and Dehghanisanij, 2019; Boccia and Punzo, 2020).

Improving agricultural water productivity is critical for achieving better water management in agriculture, ensuring food security, and reducing environmental degradation. Enhanced water productivity ensures that agricultural output increases while minimizing water overconsumption, soil degradation, and excessive use of agricultural chemicals. However, the low water productivity index in Iran's agricultural sector signals significant inefficiencies in water use, largely due to managerial shortcomings. These inefficiencies can result from a variety of factors, including outdated practices, insufficient technology, and poor water resource management. Thus, a structured program to improve agricultural water productivity is essential in Iran to reduce water consumption, balance water resources, and enhance both agricultural production and sustainability, which in turn can improve the livelihoods of farmers (Haghayeghi and Dehghanisanij, 2019).

The need for strategic water management is even more pressing on a global scale. Enhancing water productivity, defined as the ratio of crop yield to water consumed, offers one of the most promising pathways to balance escalating food needs with sustainable water use (Karimi and Jolaini, 2017). Numerous technical and managerial interventions, such as deficit irrigation, precision scheduling, and crop selection, have demonstrated potential to yield more with less water (Meena et al., 2023; Covino and Boccia, 2014). However, the relative effectiveness of these strategies can vary widely depending on local climate, soil, crop type, and socioeconomic context.

Therefore, this study aims to identify and systematically evaluate the optimal strategies for increasing water productivity in the agricultural sector by ranking available approaches for enhancing water productivity in both rainfed and irrigated agricultural systems. By integrating agronomic, environmental, and resource management criteria, the analysis seeks to pinpoint the most robust, context-sensitive options for decision-makers striving to optimize food production in the face of escalating water scarcity.

Multiple studies (Eid and Negm, 2019; Huang et al., 2021; Morsali et al., 2017; Shakoori and Morsali, 2018; Zamani et al., 2021) have attempted to identify effective solutions for enhancing agricultural water productivity and have proposed various strategies (refer to Table 1). Although previous studies have utilized a variety of quantitative and qualitative methods such as literature reviews, experiments, mathematical programming, and text analysis, they have typically focused on specific aspects of agricultural water productivity. Given the complex and multidimensional nature of agricultural water productivity, developing a framework that considers and prioritizes a comprehensive set of influencing factors remains an ongoing challenge. Additionally, devising specific strategies for each region based on its unique economic, cultural, political, and climatic conditions is essential. This study also addresses the consideration of decision-makers' natural rankings and ensures more reliable results. Therefore, the study aims to present optimal solutions for increasing agricultural water productivity using Multi-Criteria Decision Making (MCDM) techniques and by considering appropriate criteria. Rather than seeking a single best solution, it emphasizes generating a context-sensitive, technically and economically viable, and socially acceptable set of prioritized strategies for policymakers and stakeholders. In this regard, this study addresses the existing gaps in determining the necessary strategies to enhance agricultural water productivity using the Ordinal Priority Approach (OPA).

Research studies in the field of water and agriculture, such as Esfandiari et al. (2022) and Firoozzare et al. (2023), have utilized combined decision-making methods such as SWOT-AHP-FTOPSIS[1] and

[1] strengths, weaknesses, opportunities and threats (SWOT), Analytic Hierarchy Process (AHP), Fuzzy Technique for Order Performance by Similarity to Ideal Solution (F-TOPSIS).

SWOT-BWM-WASPAS.[2] However, the Ordinal Priority Approach (OPA) is a recent advancement in MCDM that offers significant advantages over other methods like TOPSIS, AHP, WASPAS, and BWM. OPA is a convenient and powerful approach that can independently estimate the weights of experts, criteria, and options. Simultaneously, as it calculates the weights of criteria and ranks options, pairwise comparisons decrease, and consistency increases. Furthermore, the strong mathematical foundation of the proposed model, combined with the aggregation of utility functions, ensures that the results are as aligned as possible with the decision-maker's preferences (Ataei et al., 2020; Boccia et al., 2013). Therefore, this study aimed to rank the criteria and alternatives related to increasing agricultural water productivity in a developing and low-income country situated in a semi-arid to arid region, namely Iran, using the OPA method. Based on the content presented, this study makes important contributions to the literature on agricultural water productivity in arid and semi-arid regions by addressing several critical gaps in a structured and integrated manner. Firstly, it introduces the application of the OPA, a relatively new MCDM method, to the field of agricultural water management. In contrast to traditional techniques such as AHP or TOPSIS, OPA simplifies the decision-making process by removing the need for complex pairwise comparisons. At the same time, it enables the simultaneous estimation of the weights of experts, criteria, and alternatives, which enhances both the consistency and interpretability of results. This provides a more intuitive and efficient framework for prioritization. Secondly, the study acknowledges the inherently multi-dimensional nature of agricultural water productivity by incorporating a broad set of evaluation criteria, including operational effectiveness, social acceptance, economic efficiency, and ecological sustainability. This comprehensive approach offers a more realistic and inclusive understanding of the factors that influence water productivity. It also fills a gap in the existing literature, where many studies have tended to focus on limited or isolated aspects of the issue. Thirdly, the research expands the empirical scope of the field by focusing on Mashhad County in northeastern Iran. This area has unique climatic, social, and economic characteristics and serves as a representative case for many other arid and semi-arid regions. By applying the OPA method in this relatively underexplored setting, the study generates context-specific findings that can inform strategies for similar regions facing comparable water management challenges. Finally, the study contributes a practical and adaptable policy framework specifically designed for developing countries. By prioritizing strategies that reflect real-world limitations such as institutional capacity, financial resources, and technical infrastructure, the study provides actionable guidance for policymakers, agricultural stakeholders, and water managers. This ensures that the proposed interventions are not only theoretically sound but also feasible and relevant in the contexts where they are most needed. The rest of the study is organized as follows: the second section, *Materials and Methods*, includes the study area, sampling method, and methodology. Results and discussion are presented in the third section. The fourth section discusses the findings.

2. Materials and methods

2.1. Study area

The study area is Mashhad County, located in Khorasan Razavi province, within a semi-arid to arid region in northeastern Iran (Fig. 1). This county covers an area of 56,536 ha of agricultural land, comprising 46,771 ha of irrigated land and 9765 ha of rainfed land. These areas possess substantial potential for both water and soil utilization. Despite the challenges posed by drought and water scarcity, agricultural water demands are met through a combination of groundwater and surface water sources, supported by 1097 deep and semi-deep wells, 351 springs, 326 qanats, and three dams (Bahraseman et al., 2024).

Given the qualitative nature of this study and its reliance on expert insights, Mashhad County was selected as the research site due to its representativeness of the arid and semi-arid regions of Iran. As the second-largest metropolitan area in the country, Mashhad plays a pivotal role in agricultural activities, population density, and institutional diversity. The region's unique socio-economic and environmental conditions provide a focused yet insightful context for identifying and prioritizing strategies to improve agricultural water productivity. Furthermore, the presence of accessible and knowledgeable stakeholders, including academic experts, policymakers, and progressive farmers, facilitated the collection of in-depth qualitative data.

A key gap addressed by this study is the absence of a structured prioritization framework for water productivity strategies in Mashhad County, which is emblematic of broader challenges in arid and semi-arid regions of Iran. Although some strategies, such as regulatory measures and educational programs, have been intermittently implemented, the lack of a cohesive, ranked, and systematic approach has limited their effectiveness. This fragmentation reflects broader challenges faced by many developing countries, where agricultural water productivity remains suboptimal due to disjointed and reactive policymaking (Haghayeghi and Dehghanisanij, 2019).

2.2. Statistical population

Sampling strategies in qualitative and quantitative research differ fundamentally in purpose and execution. While quantitative research emphasizes random sampling for statistical generalizability, qualitative research relies on purposive sampling to acquire rich, context-specific insights into the phenomenon under study (Ranjbar et al., 2012). In this study, which employed an expert-driven, qualitative MCDM framework using the OPA, expert selection followed the principles of purposive sampling, targeting individuals with specialized knowledge and direct involvement in agricultural water management in Mashhad County. A total of nine experts were interviewed, including university scholars, progressive farmers, and government officials, as presented in Table 2. Participants were selected based on their demonstrable expertise in agricultural water productivity and their familiarity with the geographical, ecological, and socio-economic conditions of the study region (Esfandiari et al., 2022). The sample size was determined according to the principle of theoretical saturation, which is widely recognized as a key standard in qualitative research (Ranjbar et al., 2012). After the ninth interview, no new strategies or insights emerged, and the information provided began to repeat. This indicated that theoretical and conceptual saturation had been reached. Similar qualitative and MCDM-based studies have employed comparable or even smaller expert panels. For instance, Aghasafari et al. (2020) interviewed 20 experts, Takeleb et al. (2020) conducted 25 interviews, Balezentis et al. (2021) included 21 interviews, Esfandiari et al. (2022) conducted 20, while Kolagar (2019) developed a prioritization framework using only 4 expert inputs. These examples support the notion that sample sufficiency in qualitative research is defined not by quantity alone but by the richness, credibility, and convergence of the data obtained. Furthermore, as the OPA method operates effectively with limited but high-quality expert input and provides consistent rankings and simultaneous weighting of experts, criteria, and alternatives, the selection of nine context-aware experts offered a methodologically sound and practically valid foundation for identifying and prioritizing strategies to improve agricultural water productivity in arid and semi-arid contexts such as Mashhad (Ataei et al., 2020; Mahmoudi et al., 2022).

In order to ensure a context-sensitive and scientifically grounded framework for evaluating interventions to improve agricultural water productivity, the identification of both the evaluation criteria and the strategic alternatives was conducted through an integrated and multi-

[2] Strengths, Weaknesses, Opportunities, and Threats (SWOT) analyses, Best-Worst Method (BWM), and Weighted Aggregated Sum Product Assessment (WASPAS).

method approach that combined expert elicitation, literature synthesis, and field-based investigation. Initially, an extensive review of previous studies related to agricultural water productivity, sustainable irrigation, and multi-criteria decision making provided a preliminary foundation for identifying potential evaluation criteria and solution strategies. These insights were subsequently enriched and validated through semi-structured interviews with nine purposively selected experts. The experts included academic scholars, senior practitioners, and policymakers who possessed deep familiarity with the agricultural, institutional, and ecological conditions of Mashhad County. Each expert was interviewed individually and responded to a series of open-ended questions aimed at eliciting their views on the key challenges affecting water productivity in the region and proposing practical and context-sensitive strategies for addressing them. To enhance the empirical grounding of the expert inputs, field studies were conducted across several agricultural zones within Mashhad County. These investigations involved direct observation of irrigation practices, infrastructure conditions, and farmer behaviors. The objectives of the fieldwork were threefold: to contextualize and validate expert opinions, to identify potential gaps between policy recommendations and on-the-ground realities, and to deepen understanding of the environmental and managerial factors influencing water productivity. The insights obtained through fieldwork were used to complement interview findings and ensure the practical relevance of the proposed strategies. Using qualitative content analysis of both interview transcripts and field observations, and supported by iterative feedback from the experts, four key evaluation criteria were identified. These were operational effectiveness, social acceptance, economic efficiency, and ecological sustainability. Simultaneously, a consolidated set of 27 actionable strategies was developed, covering a range of interventions such as institutional reforms, technology adoption, farmer training, and agronomic improvements. To maintain the integrity and diversity of expert perspectives while minimizing groupthink, each expert was subsequently asked to independently rank the identified strategies against the four criteria. This was facilitated through a structured questionnaire administered individually to all participants. The resulting rankings served as direct inputs into the OPA linear programming model, which was used to calculate the relative weights of both the experts and the strategies. This integrative and iterative process, which brought together scholarly evidence, expert knowledge, and field-based insights, ensured that the final evaluation framework was robust, contextually grounded, and practically applicable. The resulting structure provided a solid foundation for the subsequent prioritization of interventions aimed at enhancing agricultural water productivity in the study area.

2.3. Methodology

2.3.1. OPA technique

The OPA is one of the most recent advancements in MCDM methods, specifically designed to address both individual and group decision-making problems, even in the presence of incomplete or imperfect input data. This approach stands out due to its ability to deliver reliable results with minimal input requirements, such as ordinal rankings from experts, thereby eliminating the need for complex quantitative inputs. One of the primary strengths and innovations of OPA lies in its use of linear programming to derive expert weights, criteria, and alternative rankings, bypassing the need for traditional techniques such as data normalization, averaging methods for aggregating expert opinions, and pairwise comparison matrices commonly found in approaches like Analytic Hierarchy Process (AHP) or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Unlike methods like AHP or TOPSIS, which often require extensive pairwise comparisons and explicit definition of ideal and negative-ideal solutions, OPA operates based on a more intuitive framework. AHP, for instance, relies on

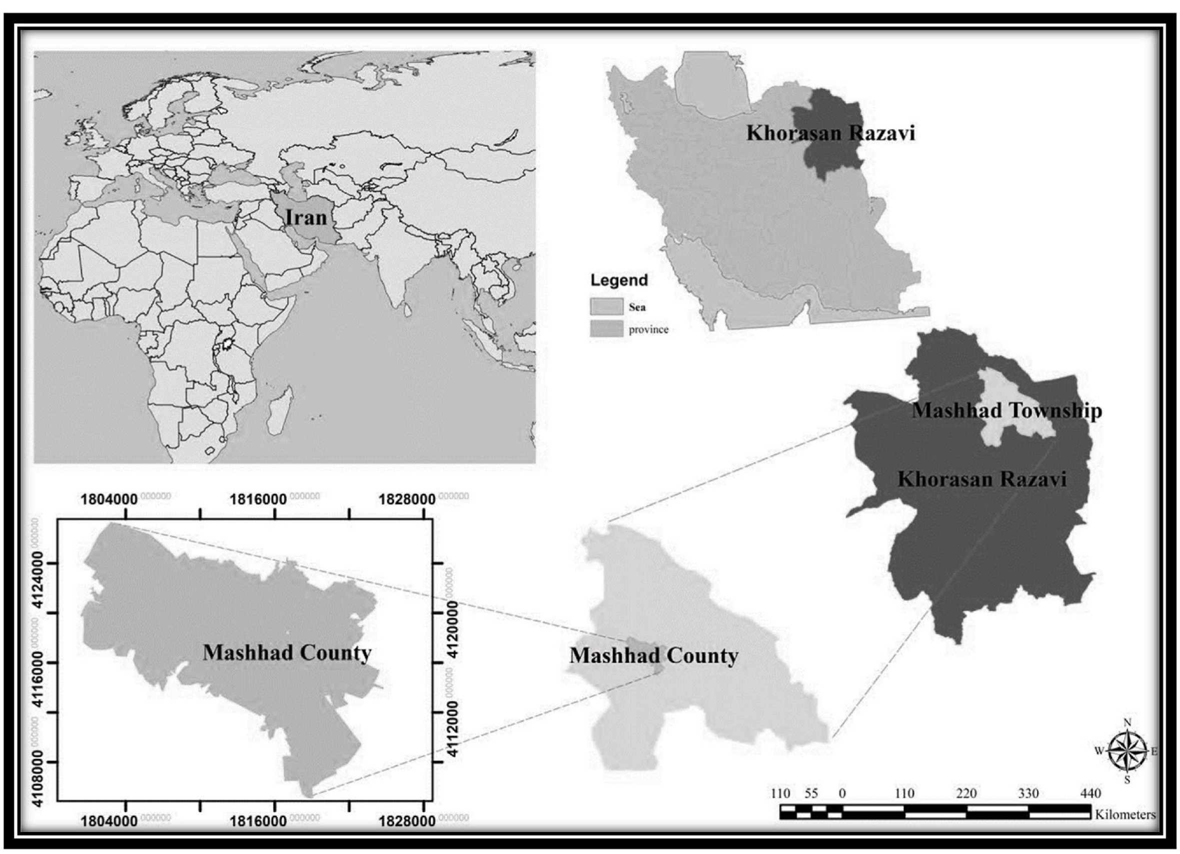

Fig. 1. Geographic location of the Mashhad County within Razavi Khorasan Province.

pairwise comparisons between criteria and alternatives, which can be time-consuming and prone to inconsistency errors due to the subjective nature of these comparisons (Wind and Saaty, 1980). Similarly, TOPSIS necessitates the calculation of distances between alternatives and ideal solutions, which can lead to the problem of normalization errors and the use of potentially incorrect ideal values, further complicating the decision-making process (Hwang and Yoon, 1981). In contrast, OPA's approach is less susceptible to such issues as it focuses solely on ordinal rankings and avoids the requirement for pairwise comparisons altogether. Another significant advantage of OPA over these methods is its inherent ability to simultaneously estimate expert weights, criteria importance, and alternative rankings within a unified model. This stands in contrast to AHP, where expert weights are determined separately and applied to the pairwise comparison process, or to TOPSIS, which focuses solely on ranking alternatives. OPA's linear programming model aggregates expert preferences in a manner that maintains consistency without requiring exhaustive comparisons or predefined ideal solutions, which often introduce artificial complexity and potential for error in traditional MCDM methods. Furthermore, OPA's simplicity and flexibility are particularly advantageous when working with incomplete or qualitative data, a common scenario in real-world decision-making. Traditional methods like AHP and TOPSIS struggle to handle incomplete or vague input data effectively, often requiring additional assumptions or adjustments to account for gaps in expert knowledge. OPA, however, operates efficiently with minimal data, relying on the ordinal rankings provided by experts, thus ensuring robust results even when detailed numerical information is not available (Mahmoudi et al., 2022). In summary, while AHP and TOPSIS are widely recognized and used in various fields, they present significant challenges in terms of cognitive burden, computational complexity, and susceptibility to inconsistencies in expert input. OPA, in contrast, offers a streamlined, error-resistant framework that avoids these pitfalls, ensuring more reliable, transparent, and interpretable results. Its ability to manage incomplete data, eliminate the need for normalization, and integrate expert judgment in a straightforward and mathematically robust manner underscores its potential as a more effective MCDM tool for complex decision-making problems in uncertain and resource-constrained environments (Ataei et al., 2020).

Following Fig. 2, the components of the OPA model are depicted, comprising three facets: experts, criteria, and alternative (Ataei et al., 2020).

The stages of performing this technique are as follows:

1. Identifying the indexes used in the research.
2. Determining and ranking the participating experts.
3. Ranking the indexes used in the research separately for each expert.
4. Solving the model written in the software and determining the weights of each indexes and expert.

In the OPA technique, after determining the number of participating experts, a structured selection process was undertaken to ensure the reliability and validity of the input data. Expert selection was based on a clearly defined set of criteria, including: (1) academic qualifications in relevant disciplines such as agricultural engineering, water resource management, or environmental sciences; (2) length and relevance of professional experience, particularly in projects focused on agricultural water use; (3) involvement in policy-making, extension services, or research activities related to water productivity in arid and semi-arid regions; and (4) demonstrated familiarity with the specific environmental, socio-economic, and institutional conditions of Mashhad County. All selected experts were assigned equal weights in the OPA linear programming model to ensure balanced representation of diverse perspectives. This approach ensured that each expert's opinion had an equivalent influence on the decision-making outcomes. Once expert selection was completed, the OPA model was formulated according to the following linear programming structure:

$$
\begin{aligned}
&\text{Max } Z \\
&\text{s.t.} \\
&Z \leq i\Big(j\Big(r\Big(W_{ijk^r} - W_{ijk^{r+1}}\Big)\Big)\Big) \quad \forall i, j, k \text{ and } r \\
&Z \leq ijmW_{ijk^m} \quad \forall i, j \text{ and } k \\
&\sum_{i=1}^{p}\sum_{j=1}^{n}\sum_{k=1}^{m} \mathrm{Wijk} = 1 \\
&\mathrm{Wijk} \geq 0 \quad \forall\, \mathrm{i, j \text{ and } k} \\
&\text{where Z : Unrestricted in sign}
\end{aligned}
\tag{1}
$$

In this model, parameters and variables are defined as follows (Table 3):

After solving the model, the weights of alternative, criteria, and experts are calculated sequentially through the following relationships (Maleki et al., 2022).

$$Wk = \sum_{i=1}^{p}\sum_{j=1}^{n} Wijk \;\forall\, k \tag{2}$$

$$\mathrm{Wj} = \sum_{i=1}^{p}\sum_{k=1}^{m} \mathrm{Wijk} \;\forall\, \mathrm{j} \tag{3}$$

$$\mathrm{Wi} = \sum_{j=1}^{n}\sum_{k=1}^{m} \mathrm{Wijk} \;\forall\, \mathrm{i} \tag{4}$$

Subsequently, these weights can be utilized for decision-making and ranking of criteria, experts, and alternatives. Fig. 3 illustrates the flowchart of the OPA.

From a methodological perspective, the Ordinal Priority Approach establishes a rigorously structured and fully transparent framework for converting expert judgments into a defensible hierarchy of strategies. In the initial phase, experts independently ranked the four evaluation dimensions (operational feasibility, social acceptance, economic efficiency, and ecological sustainability) according to their informed judgment of relative importance. These ordinal rankings were then directly incorporated into the OPA linear-programming model, which computes a unique set of normalized criterion weights by optimizing consistency across all expert inputs. This algorithmic derivation of weights obviates any reliance on arbitrary scaling or manual aggregation procedures. In the subsequent phase, the same panel applied ordinal assessments to all twenty-seven candidate strategies under each criterion, thereby minimizing cognitive burden by avoiding exhaustive

Table 2
Classification of participants completing the questionnaire.

Participant group	Specific roles/Fields	Number of participants
Academia	Professor of Water Engineering; Professor of Environmental Science; Professor of Agricultural Economics	3
Governmental organizations	Manager, Department of Environment (Mashhad); Managers, Khorasan Razavi Regional Water Company; Managers, Khorasan Razavi Agriculture Organization	5
Exemplary farmers	Progressive farmers with demonstrated expertise in agricultural water productivity	1
Total		9

pairwise comparisons. The OPA solver converted each strategy's rank ordering into a normalized performance vector, multiplied these values by the previously derived criterion weights, and summed the results to generate a single composite score for each alternative. Because both criterion weighting and strategy evaluation are executed end to end by the OPA algorithm, the entire process remains fully traceable to its underlying mathematical logic. Strategies demonstrating superior performance in the most heavily weighted dimensions naturally ascend to the top of the final list, while those scoring primarily in less influential areas occupy lower positions. This two-stage, optimization-driven procedure thus provides a transparent, replicable, and theoretically sound justification for the priority ordering presented in the manuscript (Ataei et al., 2020). To ensure computational precision and reproducibility, the OPA model formulation and ranking calculations were implemented in the Python programming language. The use of Python facilitated accurate linear programming computations, automated weight estimation, and efficient handling of ordinal data provided by experts.

3. Results and discussion

Based on field studies, library research, interviews with experts, and relevant literature, this study proposed four criteria (Table 4 and Fig. 4) and 27 strategies (Table 5 and Fig. 5) to increase agricultural water productivity. According to the OPA technique, among the proposed criteria, "operational effectiveness" (C2) was assigned the highest weight (0.319). Experts in this study pointed out that in developing countries, financial, technical, and institutional resources for implementing strategies are often limited. Therefore, strategies that are technically, institutionally, and organizationally feasible, and can effectively save water and improve agricultural water productivity, should be prioritized. The criterion of "social acceptance," with a weight of 0.280, was ranked as the next priority. Although "social acceptance" received a slightly lower weight than "operational effectiveness," it remains a highly important criterion. Experts acknowledged that in developing countries, operational feasibility often determines the immediate applicability of strategies. However, they also emphasized that social acceptance is critical for securing public support and ensuring the successful long-term implementation of strategies. Thus, while ranked second, "social acceptance" complements "operational effectiveness" by enhancing the practicality and sustainability of selected strategies. "Economic efficiency," with a weight of 0.244, ranked third. Experts emphasized the prioritization of strategies that not only increase agricultural water productivity but are also economically beneficial. A study by Domini et al. (2017) in Tanzania highlighted the importance of cost considerations and stressed the necessity of promoting the adoption of low-cost solutions. Finally, "ecological sustainability," with a weight of 0.155, was ranked as the lowest priority. Although experts recognized that ecological sustainability may hold relatively lower immediate importance, this should not be interpreted as a lack of significance. Its fourth-place ranking reflects the experts' judgment that, given current institutional, technical, and economic constraints, strategies that are operationally feasible and socially acceptable must be prioritized for successful implementation. Nevertheless, ecological sustainability remains a vital long-term objective, and its inclusion as a core criterion underscores its essential role in agricultural water productivity planning in Mashhad County.

In this case study, experts were tasked with scoring 27 strategies based on five criteria (i.e., C1, C2, C3, C4, and C5). In Table 5, the ranking and weight of the strategies using OPA are reported. The rankings listed in Table 5 are also shown in Fig. 5 for better clarity. Based on the results, Institutional and Policy Interventions (IPI), such as legal and regulatory reforms in water management (A4), upgrading the water information bank (A21), and creating water pricing and trading mechanisms (A17), have been given higher priority compared to other strategies. This strategy in a developing country facilitates the creation of a suitable environment for the implementation of other strategies to increase agricultural water productivity. Capacity-building and Awareness Interventions (CAI), such as training and empowering farmers in efficient water management and promoting modern technologies (A8), were given next priorities. This is because developing the necessary understanding and skills among farmers is a prerequisite for adopting other strategies to increase agricultural water productivity. Irrigation Technology Interventions (ITI), such as adopting more efficient irrigation systems (A7) and using smart technologies for precise irrigation management (A1), were given next priorities. The experts in this study stated that these strategies could lead to direct and significant savings in water use and, consequently, an increase in agricultural water productivity. Agronomic Interventions (AI) and genetic interventions (GI), such as selecting drought-resistant varieties and optimizing water (A5) and soil management through conservation agriculture (A19), were also given lower priority. Finally, the Water Resource Management Interventions (WRMI), such as implementing water storage techniques (A26), were given the lowest priority. The experts believed that these strategies could improve the availability of water. Subsequently, based on the identified and prioritized criteria, 27 strategies for increasing agricultural water productivity were proposed and prioritized, which we will discuss in detail.

Rank 1: Legal and regulatory reforms in water management

Experts argue that legislative and regulatory reforms are essential for

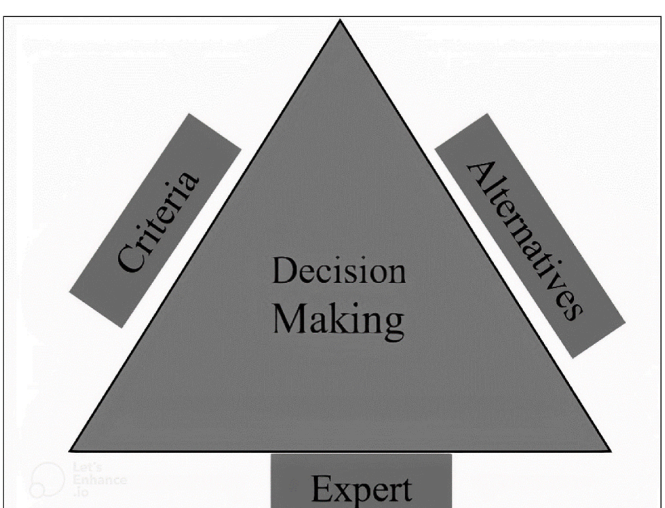

Fig. 2. The decision-making components in the OPA model Source (Ataei et al., 2020):

Table 3
Sets, indexes, and variables used in the OPA.

Sets	
I	Set of experts $\forall i \in$ I
J	Set of criteria $\forall j \in$ J
K	Set of alternatives $\forall k \in$ K
Indexes	
i	Index of the experts (1, …, p)
j	Index of preference of the criteria (1, …, n)
k	Index of the alternatives (1, …, m)
Variables	
Z	The objective function
Wijk r	Weight (importance) of kth alternative based on jth criterion by ith expert at rth rank
Parameters	
i	The expert's rank i
j	The criterion's rank j
r	The alternative's rank k

Source: Ataei et al. (2020).

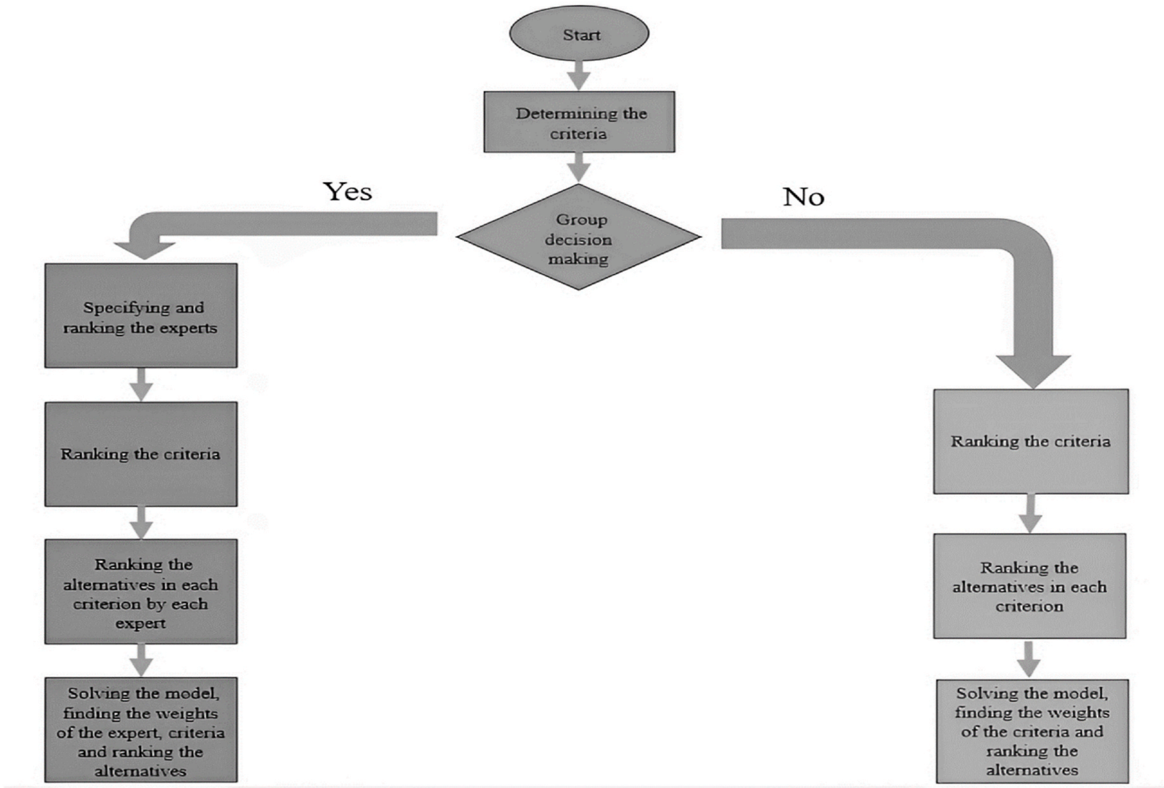

Fig. 3. Flowchart of the OPA source (Ataei et al., 2020):

enhancing agricultural water productivity, particularly in developing countries like Iran. These reforms include equitable allocation of water rights, stronger oversight of water resources, implementation of effective economic instruments, legal incentives for optimal water use, and increased involvement of local communities. Mirnezami and Bagheri (2017) further emphasize the necessity of restructuring water governance to ensure the sustainability of groundwater resources. Meena et al. (2019) identified political factors, such as unregulated groundwater extraction supported by subsidized electricity, as the primary cause of rapid groundwater depletion in various regions of India.

Rank 2: Upgrading the water information bank

Experts highlight the importance of upgrading water information banks as a strategy to improve agricultural water productivity. These systems provide accurate and timely data, helping farmers understand the actual water requirements of their crops and implement smart irrigation techniques. Furthermore, water information banks aid in optimizing water resource management and predicting and mitigating water crises. These conclusions align with the findings of Gakuru et al. (2009), who emphasized the role of agricultural information websites in their research.

Rank 3: Policy-making and implementing economic instruments such as water pricing in agriculture and water markets

Table 4
Determining the weights and ranking of criteria using OPA.

Criteria		Weights	Ranking
C1	Ecological sustainability	0.155	4
C2	Operational effectiveness	0.319	1
C3	Social acceptance	0.280	2
C4	Economic efficiency	0.244	3

Experts propose that implementing economic instruments, such as pricing water based on its value and establishing water markets, can enhance agricultural water productivity. By assigning appropriate prices and facilitating the exchange of water rights, farmers are encouraged to use water more efficiently. This, in turn, can lead to technological improvements and crop diversification. This approach is supported by studies such as Molle et al. (2008) and Dinar (2000), which advocate for increased water productivity through efficient resource management.

Rank 4: Improving agricultural trade and marketing

Enhancing agricultural trade and marketing can contribute to higher water productivity by enabling access to higher-value markets, reducing post-harvest losses, encouraging crop diversification toward more water-efficient species, and providing incentives for investment in water-saving technologies. It also supports a transition to high-value horticultural products. According to the study by Haghayeghi and Dehghanisanij (2019), improved agricultural trade and marketing were identified as critical strategies for boosting water productivity in the agricultural sector of Khorasan Razavi Province. This finding supports the outcomes of the current study.

Rank 5: Attention to and utilization of virtual water solutions

Although often associated with the concept of virtual water trade, the use of virtual water strategies can significantly enhance agricultural water productivity. Through virtual water trade, countries with limited water resources can fulfill their water demands by importing water-intensive products, thereby reserving local water for higher-value uses such as irrigation of strategic crops. Yang and Zehnder (2007) highlighted the importance of integrating virtual water considerations into water resource management.

Rank 6: Investment in research and development

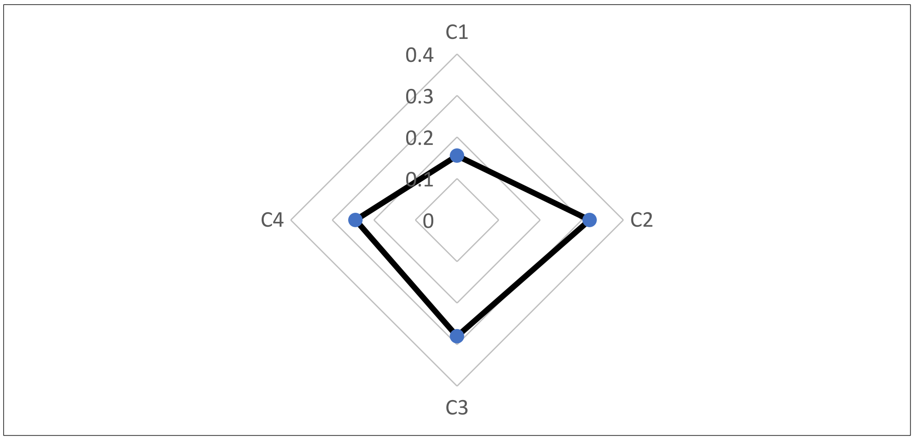

Fig. 4. Ranking of criteria using OPA.

Experts emphasize that investing in the research and development of irrigation technologies, improving drought-resistant crop varieties, enhancing land and water management practices, and advancing water purification and recycling technologies can significantly improve agricultural water productivity in developing regions such as Mashhad, Iran. A recent study by Mohammadi and Pourian (2023) highlighted the crucial role of knowledge-based research companies in boosting agricultural productivity in Iran. Furthermore, Meena et al. (2023) recommended that research activities focus on practical solutions for improving water productivity, including the use of remote sensing, centralized Internet of Things systems, evaluation of water-efficient products, and assessment of crop suitability.

Rank 7: Establishing Water User Associations (WUAs)

According to experts in this study, the establishment and strengthening of Water User Associations (WUAs) can play a vital role in increasing agricultural water productivity in Iran, especially in Mashhad. These associations can offer solutions tailored to local conditions, promote coordination in water use, and encourage farmer engagement by reinforcing local responsibility. Additionally, they help enhance the management of irrigation infrastructure. Ghareghani and Hayati (2012) emphasized the importance of WUAs as a practical strategy to boost farmer participation in agricultural water management.

Rank 8: Training and empowering farmers

Training and empowering farmers can significantly enhance agricultural water productivity in multiple ways. These include increasing farmers' awareness of water-saving practices, transferring modern irrigation technologies, providing education in water resource management, enhancing motivation to reduce water consumption, and strengthening both technical and managerial capacities. Nabiafjadi et al. (2015) and Forouzani and Karami (2011) noted that training plays a key role in adopting new technologies for sustainable water management, leading to long-term environmental, economic, and social benefits in agriculture. In addition, Barman et al. (2017) also emphasized the importance of farmer education in improving water productivity.

Rank 9: Land consolidation in agricultural areas

Land consolidation in agricultural regions can contribute to improved water productivity in developing countries through several mechanisms. These include achieving economies of scale, enabling the use of advanced irrigation systems, enhancing water management through coordinated planning, supporting the development of shared infrastructure, and improving farmers' access to essential inputs and water resources. Moradinejad and Eslampour (2018) emphasized that land consolidation is critical to increasing agricultural water efficiency.

Rank 10: Establishing water police and other regulatory institutions

Experts argue that establishing water police and other regulatory institutions is essential for improving agricultural water productivity in Mashhad. These entities help protect water resources and ecosystems by monitoring water usage, managing reservoirs, reducing pollution, and preventing overexploitation. Akbarzadeh et al. (2020) stressed the potential of water police to regulate and control groundwater extraction. They also highlighted their role in supervising facilities, infrastructure, and practices that affect the sustainability and quality of water systems. These insights are consistent with the findings of the current study.

Rank 11: Installation of water meters and volume-based water delivery to farmers

According to experts in this study, installing water meters and delivering water to farmers based on volume can help control excessive water extraction and enhance agricultural water productivity. This approach allows farmers to manage their water usage more accurately, resulting in reduced wastage and improved efficiency. Qobadpour et al. (2018) and Derakhshan and Omranian Khorasani (2019) have identified this method as an effective tool for controlling water use, particularly through the installation of smart meters on groundwater wells.

Rank 12: Improving the design and maintenance of irrigation infrastructure

The findings indicate that improving the design and maintenance of irrigation infrastructure can enhance water productivity in agriculture in Mashhad County. This improvement helps reduce water losses due to leakage and evaporation, while also increasing the efficiency of water conveyance and distribution among farmers. Meena et al.,)2023) identified inefficient infrastructure as a major contributor to water wastage and reduced productivity in the agricultural sector.

Rank 13: Development and application of efficient and advanced irrigation systems

Experts in this study suggest that adopting advanced irrigation systems such as drip and rainwater irrigation can contribute significantly to enhancing water productivity in Mashhad County. These systems minimize water loss and optimize water usage, leading to higher yields and better efficiency. Meena et al.,)2023) emphasized the effectiveness of methods such as drip irrigation and regulated deficit irrigation in

Table 5
Weighting and ranking of strategies to increase agricultural water productivity using OPA.

Types of interventions	Alternatives (Strategies)		Weights	Ranking
Irrigation Technology Interventions (ITI)	A1	Utilizing smart technologies for precise irrigation management	0.03472	14
Institutional and Policy Interventions (IPI)	A2	Investment in research and development	0.04568	6
Capacity-building and Awareness Interventions (CAI)	A3	Establishing Water User Associations (WUAs)	0.04500	7
Institutional and Policy Interventions (IPI)	A4	Legal and regulatory reforms in water management	0.06427	1
Agronomic Interventions (AI)	A5	Selecting low-water-demand products	0.03199	17
Water Resource Management Interventions (WRMI)	A6	The expansion of livestock, poultry, and aquaculture sectors	0.02954	22
Irrigation Technology Interventions (ITI)	A7	Development and application of efficient and advanced irrigation systems	0.03525	13
Capacity-building and Awareness Interventions (CAI)	A8	Training and empowering farmers	0.04357	8
Institutional and Policy Interventions (IPI)	A9	improvement agricultural trade and marketing	0.04759	4
Agronomic Interventions (AI)	A10	Cultivation in controlled environments	0.03440	15
Institutional and Policy Interventions (IPI)	A11	Installation of water meters and delivery of water to farmers based on volume	0.03950	11
Irrigation Technology Interventions (ITI)	A12	Deficit Irrigation	0.03148	18
Agronomic Interventions (AI)	A13	Improved methods of cultivating crops in agriculture	0.03147	19
Water Resource Management Interventions (WRMI)	A14	Optimal allocation of water resources	0.02736	25
Water Resource Management Interventions (WRMI)	A15	Improving the design and maintenance of irrigation infrastructure	0.03693	12
Institutional and Policy Interventions (IPI)	A16	Attention to and utilization of virtual water solutions	0.04588	5
Institutional and Policy Interventions (IPI)	A17	Policy-making and implementing economic instruments such as water pricing in agriculture and water markets	0.04869	3
Agronomic Interventions (AI)	A18	Land leveling in agriculture	0.03242	16
Agronomic Interventions (AI)	A19	Optimizing water and soil management with conservation agriculture	0.03108	20
Institutional and Policy Interventions (IPI)	A20	Establishing water police and other regulatory institutions	0.04000	10
Institutional and Policy Interventions (IPI)	A21	Upgrading the water information bank	0.04953	2
Institutional and Policy Interventions (IPI)	A22	Land consolidation in agricultural areas	0.04298	9
Institutional and Policy Interventions (IPI)	A23	The development of an Integrated Farming Systems	0.02849	24
Agronomic Interventions (AI)	A24	Seed Priming	0.01902	27
Agronomic Interventions (AI)	A25	improvement and enhancement of mechanization	0.02934	23
Water Resource Management Interventions (WRMI)	A26	Water harvesting and storage techniques	0.02335	26
Agronomic Interventions (AI)	A27	Improving crop rotation and intercropping	0.03047	21

increasing crop yield and improving water productivity. These findings are consistent with the present study. In addition, (Kulkarni, 2011) highlighted the importance of adopting irrigation technologies for improved water management.

Rank 14: Utilizing smart technologies for precise irrigation management

According to the experts, smart technologies can play a significant role in precision irrigation and improved water productivity. These technologies include the use of sensors and sensor networks to increase accuracy in irrigation, reduce water loss by detecting inefficiencies, enable real-time irrigation planning based on live data, and enhance overall farm-level water management. (Meena et al., 2023) support these views. Similarly, (Dassanayake et al., 2009) demonstrated that connected sensor networks led to significant water savings in Australia compared to traditional border irrigation. (Ojha et al., 2015) also presented survey results from India and other countries showing that the use of wireless sensor networks can reduce water use by up to 30 percent compared to conventional irrigation systems.

Rank 15: Cultivation in controlled environments

Cultivating crops in controlled environments, such as greenhouses, can greatly enhance water productivity in developing countries. Experts in this study identified several advantages of controlled cultivation, including reduced water wastage through precise environmental regulation, the use of advanced irrigation systems, and the overall improvement of water use efficiency. (Lakhiar et al., 2018) described greenhouse cultivation as a critical strategy for conserving soil moisture and reducing water demand, which supports the current study's conclusions.

Rank 16: Land leveling in agriculture

Experts in this study recommend precise land leveling as a means of improving agricultural water productivity. Garnaik et al.,)2022) found that improper land leveling can cause either over-irrigation or under-irrigation in different parts of a farm, leading to uneven crop performance and decreased water use efficiency.

Rank 17: Selecting low-water-demand products

Selecting drought-resistant crops, including native plants and those adapted to local climatic conditions, can significantly increase agricultural water productivity. Experts in this study believe that by choosing plants suitable for the environmental conditions of the region, the need for additional irrigation naturally decreases, resulting in increased water productivity. Ali and Talukder)2008) also stated in their study that

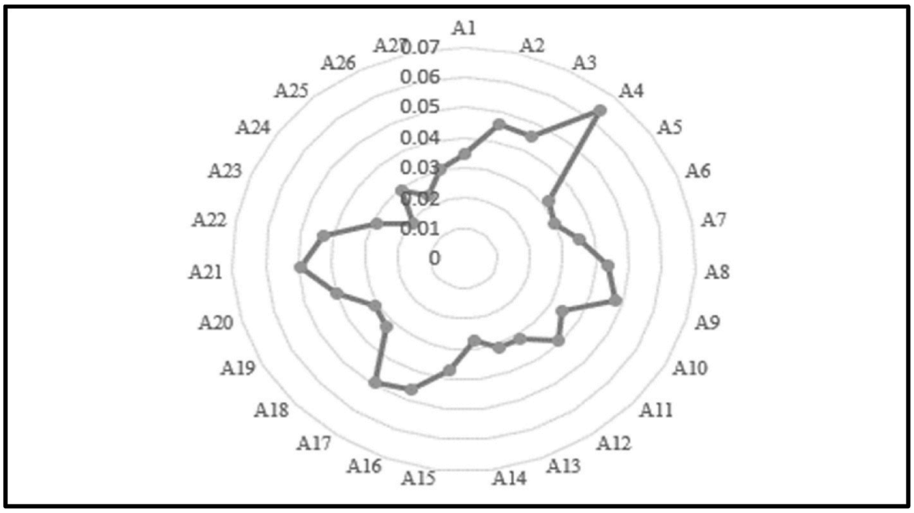

Fig. 5. Alternatives ranking using OPA.

selecting a low-water-demand crop can save water and utilize the saved water for irrigating additional lands, thereby increasing agricultural water productivity. (Bakhtyari et al., 2023) also emphasized the impact of modifying cropping patterns on agricultural water productivity.

Rank 18: Deficit irrigation

Water-saving methods involve reducing irrigation during specific stages of the crop cycle, especially when the crop is less sensitive to water scarcity. In this approach, irrigation is applied only during vital stages of the crop's life to fulfill its water needs, while in other stage, including critical stages of crop development, less irrigation is applied. This approach can be implemented through various techniques, including alternate wetting and drying, reducing irrigation depth, skipping irrigation during less critical stages of crop growth, and irrigating the crop only in alternate rows (Du et al., 2015; Kang et al., 2000). (Fereres and Soriano, 2007) introduced this method as an effective measure to increase water productivity in their study.

Rank 19: Improved methods of cultivating crops in agriculture

Conventional methods of flat planting and flood irrigation may encounter problems such as excessive flooding and over-irrigation, which can lead to crop failure. However, improved methods such as planting in furrow irrigation beds (FIRB) and other management techniques can bring about significant improvements in agricultural crop performance and savings in water, seeds, fertilizers, and herbicides (Meena et al., 2023). Multiple studies have reported significant water savings of up to 50 % in wheat and pearl millet cultivation using the FIRB system compared to flat planting (Garnaik et al., 2022; Jat et al., 2021).

Rank 20: Optimizing water and soil management with conservation agriculture

Optimizing water and soil management through appropriate soil conservation methods, establishing permanent vegetation cover, and utilizing organic materials can significantly increase water retention in the soil. This can enhance nutrient uptake by plants and contribute to higher agricultural water productivity with the same input of water. Patnaik et al. (2022) emphasized the role of conservation agriculture in increasing water productivity. Additionally, Phogat et al. (2020) stated that zero tillage is a simple technology that reduces evaporation losses, regulates soil temperature, increases soil organic carbon, enhances crop yield, and leads to increased agricultural water productivity.

Rank 21: Improving crop rotation and intercropping

In this study, experts emphasized that using appropriate crop rotation patterns and simultaneous cultivation of crops can help improve agricultural water productivity in Mashhad. These methods contribute to maintaining soil fertility, controlling pests and diseases, better water resource management, and reducing water use while increasing productivity. Mao et al. (2012) stated that mixed cropping can be a sensible strategy to reduce the need for irrigation water. For example, the rational arrangement of mixed cropping strips, such as maize-pea intercropping with four rows of maize and four rows of peas, can reduce water use by 10.2–13.7 % compared to pure cropping. Additionally, Monckton and Mendham (2022) noted that farm agroforestry leads to increased farm productivity, improved water quality, soil enhancement, drought resilience, and increased biodiversity.

Rank 22: The expansion of livestock, poultry, and aquaculture sectors

The expansion of livestock, poultry, and aquaculture sectors can act as a complementary or even substitutive pathway for reducing the cultivation of water-intensive crops such as alfalfa, sugar beet, and forage maize, which consume large volumes of irrigation water while offering relatively low economic returns per unit of water. By increasing the availability of alternative protein sources, this strategy can shift production away from these water-demanding crops. Furthermore, integrating these subsectors into the broader agricultural system promotes diversification and resilience. For instance, mixed crop-livestock systems may optimize nutrient cycling and reduce input dependency. In regions facing acute water scarcity, such integration supports higher overall water productivity by redirecting water use toward sectors with better output-to-input ratios. This approach not only enhances food security through diversified protein supply but also contributes to more sustainable water resource management. Haghayeghi and Dehghanisanij (2019) identified the expansion of livestock, poultry, and aquaculture sectors as one of the most important solutions for increasing agricultural water productivity in Khorasan Razavi Province.

Rank 23: Improvement and enhancement of mechanization

The mechanization of agriculture can improve agricultural water productivity in several ways. The use of mechanized equipment for plowing, planting, and harvesting can reduce water losses, as these tools allow farmers to carry out these tasks in a timely and precise manner. Additionally, mechanization can help increase land productivity. Advanced planting machines can increase plant density and improve yields, ultimately leading to a reduction in the amount of water required to produce each unit of output. Haghayeghi and Dehghanisanij (2019) identified the enhancement of agricultural mechanization as one of the most important solutions for increasing agricultural water productivity in Khorasan Razavi Province. This finding is consistent with and confirms the results of the present study.

Rank 24: The development of an Integrated Farming Systems

An Integrated Farming Systems, combining various activities such as crop cultivation, livestock farming, aquaculture, and related activities, can help improve agricultural water productivity and have positive effects. This system can optimize water resources, facilitate efficient water resource management, prevent water wastage, and ultimately enhance productivity in agriculture. Bhuvaneswari et al. (2020) showed that integrated agricultural systems lead to increased physical and economic water productivity. Nanda and Adamala (2019) also emphasized the importance of integrated agricultural systems in increasing productivity in their research.

Rank 25: Optimal allocation of water resources

Optimal allocation of water resources refers to determining the optimal amount of water from surface and groundwater sources to meet various needs in watershed areas (Alami et al., 2015). Therefore, an allocation model can be used to optimally distribute limited water resources among multiple users. Reallocating water from low-value to high-value crops can increase the economic productivity of water. In a study by Sahabifard et al. (2024), the importance of optimal allocation of water resources on water productivity and savings was emphasized.

Rank 26: Water harvesting and storage techniques

Techniques such as farm ponds, reservoirs, and groundwater recharge are vital for increasing access to water and reducing scarcity in agriculture. These methods collect rainwater and provide a reliable source during dry periods, thus supporting crop growth and productivity. By capturing and storing water, they reduce dependence on unpredictable rainfall patterns and surface water, ensuring a consistent water supply. Additionally, these techniques facilitate groundwater recharge, which is crucial for regions dependent on irrigation. Meena et al. (2023) stated that effective and efficient rainwater harvesting and runoff control can enhance agricultural water productivity in areas experiencing a decline in groundwater levels.

Rank 27: Seed priming

In dry and semi-arid regions with limited access to water, improper germination and weak crop establishment pose unavoidable challenges. A suggested solution is the use of seed priming, which enhances germination, plant growth, crop yield, and irrigation water quality. This method is particularly effective for grains, legumes, and vegetables, facilitating early crop establishment and increasing plant resistance (Roqueiro et al., 2012). Multiple studies, such as Meena et al. (2015) and Shabbir et al. (2014), have also emphasized the role of seed priming in enhancing water productivity.

While all the proposed strategies contribute meaningfully to the improvement of agricultural water productivity, certain interventions such as seed priming, water harvesting and storage techniques, integrated farming systems, and advanced mechanization received lower priority rankings. This does not imply a lack of relevance or effectiveness; rather, it reflects the expert panel's context-based assessment of feasibility and immediate applicability. In the case of Mashhad County, many of these lower-ranked strategies require considerable financial investment, long-term planning, cross-sectoral coordination, or technological capacity that may not yet be fully developed. Experts therefore favored strategies that are operationally feasible, institutionally supported, and capable of generating tangible outcomes within a shorter time horizon. As such, the lower rankings assigned to these strategies are not due to their intrinsic limitations, but rather to real-world constraints that may hinder their immediate implementation. Importantly, these strategies still represent valuable long-term options that should be revisited as local capacities evolve.

Although some strategies, such as regulatory interventions and farmer training programs, are sporadically implemented in the study area of Mashhad County, which is situated within a developing country context, the lack of a coherent, prioritized, and organized approach significantly limits their effectiveness. This fragmentation reflects broader structural challenges observed in many developing nations, where agricultural water productivity remains low due to uncoordinated and reactive policymaking. By employing the OPA, this study filled this critical gap by offering a systematic ranking of strategies based on context-specific criteria. This structured prioritization enabled decision-makers to not only identify which interventions were most important but also to determine the appropriate sequence for their implementation. As a result, the study provided the foundation for designing a phased and goal-oriented water management policy framework tailored to the needs of arid and semi-arid regions.

4. Conclusion

This study utilized the Ordinal Priority Approach (OPA) to identify and rank the most effective strategies for enhancing agricultural water productivity in arid and semi-arid regions, with a particular emphasis on Mashhad, Iran. By conducting expert interviews and applying weighted criteria, strategies were evaluated based on operational efficiency, social acceptance, economic feasibility, and environmental sustainability. The results revealed that institutional and policy interventions were prioritized above all other categories in the Mashhad district. This finding suggests that in other developing countries with similar climates, policymakers should concentrate on formulating and implementing effective policies, regulations, and institutional frameworks to promote water conservation and improve efficiency in the agricultural sector. Policymakers should engage a broad spectrum of stakeholders, including farmers, local communities, extension services, and researchers, in the development and implementation of water management policies. Such collaboration ensures that interventions are contextually relevant and widely supported.

Next in priority were capacity-building and awareness-raising interventions. It is recommended that educational programs, workshops, and public awareness campaigns be developed to help farmers, policymakers, and other stakeholders understand the significance of water conservation and adopt better management practices. These initiatives can emphasize the advantages of sustainable practices and encourage collective efforts to enhance water productivity. Furthermore, strengthening agricultural extension services is crucial for providing timely technical support and training on water-saving methods. Extension officers can play a vital role in knowledge transfer and encouraging adoption. The establishment of farmer field schools is also encouraged, as they offer platforms for peer learning and expert guidance on efficient water management techniques.

Interventions focused on irrigation technology development were ranked next. In this context, policymakers are advised to offer incentives or subsidies for the adoption of advanced irrigation systems, such as drip irrigation, and to promote best practices that improve irrigation efficiency. Support for research and innovation in irrigation technologies is also essential, as it can lead to the discovery of more efficient and environmentally friendly solutions.

Agronomic and genetic strategies were placed lower in priority, followed by water resource management interventions, which received the least priority. Nevertheless, these approaches can still contribute meaningfully. For example, integrating crop-livestock systems can enhance overall resource efficiency and productivity. Practices such as mulching, cover cropping, and conservation tillage should be encouraged to retain soil moisture and reduce evaporation. Precision agriculture methods, including site-specific irrigation and nutrient management, can further optimize water usage in farming.

This study offers several contributions. From a novelty standpoint, it applies the OPA method to prioritize water productivity strategies in the context of a developing country. Theoretically, it presents a framework for evaluating interventions based on operational, economic, social, and environmental dimensions. Practically, it provides actionable recommendations for policymakers and stakeholders to improve agricultural water productivity, enhance food security, and support sustainability. Overall, the study presents a unique, multidimensional approach to boosting water productivity in agriculture, offering insights valuable for both theoretical and applied domains.

4.1. Limitations of the research and suggestions for future studies

Given that this research was conducted in a developing country, the generalizability of the findings may be limited. Future studies could apply this framework in different regions and compare the results to identify regional factors that influence strategy prioritization. Additionally, exploring the applicability of the proposed framework in other semi-arid contexts would provide further insight into its versatility. This study's use of the innovative OPA method within the MCDM domain opens new avenues for research. Future studies are encouraged to integrate OPA with other MCDM techniques and conduct comparative evaluations. Such analyses could offer a deeper understanding of OPA's robustness and utility. Moreover, long-term evaluations of implemented strategies across different regions should be conducted to assess their sustainability and effectiveness. Monitoring these outcomes over time can reveal both benefits and challenges in practice. Finally, ensuring coordination between agriculture, water resource management, and environmental sectors is essential. Policy coherence and integrated approaches can significantly enhance the impact of strategies aimed at improving water productivity and agricultural sustainability.

CRediT authorship contribution statement

Sasan Esfandiari Bahraseman: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Firoozzare:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Conceptualization. **Flavio Boccia:** Writing – original draft, Supervision, Methodology, Funding acquisition. **Fateme Pourmohammad:** Writing – review & editing, Software, Investigation, Data curation. **Amir Hossein Ameri:** Writing – review & editing, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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