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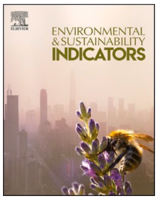

Evaluating climate change adaptation options in the agriculture sector: A PROMETHEE-GAIA analysis

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ABSTRACT

Mitigating maladaptation and effectively managing climate risks are crucial components of strategic planning in agriculture amidst climate change. Evaluation serves as a pivotal element in this process, facilitating the identification of effective adaptation strategies tailored to local contexts. Consequently, it's imperative to thoroughly evaluate these strategies to ensure their success and resilience. The current study evaluated adaptation methods tailored to the local context in southwest Iran across three categories-crop, farm, and water management-employing Multi-Criteria Decision-Making (MCDM) and the PROMETHEE-GAIA. Sensitivity analysis was performed during the AHP (Analytical Hierarchy Process) stage to confirm the criteria weights and in the PROMETHEE to confirm the ranking. A set of eight criteria, including effectiveness/importance, affordability, institutional feasibility, technical feasibility, social feasibility, traditional acceptance, flexibility, and environment side effects (positive) were applied to evaluate the adaptation measures. Our results indicated the three highest rankings in each set of measures, as follows: i) crop management—relay intercropping, change of crop type, and mixed intercropping; ii) farm management—pest and disease management, weed control, and crop rotation; iii) water management—lining water canals or covering their earth floors with nylon, using pipes rather than open canals to transfer water to the field, and increasing the time intervals between irrigations to deal with water shortages. The outcomes underscore the urgency of formulating region-specific adaptation policies that align with local expertise and contextual needs. By prioritizing the identified effective strategies, policymakers can enhance resilience against water scarcity in southwest Iran. Moreover, the study highlights the importance of ongoing evaluation and adaptation, emphasizing the dynamic nature of climate challenges and the need for continuous refinement of adaptive policies.

1. Introduction

Adaptation has stood for many years as a critical element in the comprehensive, long-term global response to climate change, safeguarding individuals, livelihoods and ecosystems (UNFCCC, 2023; Yazdanpanah et al., 2023a). It is defined as purposeful actions that enhance the coping capacity and resilience of different systems to climate change (El-Batran and Aboulnaga, 2015; Yazdanpanah et al., 2024; Shariatzadeh and Bijani, 2022; Savari and Amghani, 2022). Response to climate change encompasses a board spectrum of options, as outlined by Singh (2015) in the "response or adaptation continuum". The best optimal state of response resides at the end of the spectrum, characterized by effective or successful adaptation, while the undesirable situation of maladaptation is situated at the opposite end. As adaptation entails a movement toward sustainable livelihoods, maladaptation poses a considerable risk of system vulnerabilities (Singh et al., 2018). This underscores the critical need to ensure that economic resilience in rural environments signifies "successful adaptation," not merely "adaptation" (Aryal et al., 2020). Successful adaptation as articulated by de França Doria et al. (2009), involves any adjustment in

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response to climate change that effectively reduces the associated risks or vulnerability to predetermined level, without compromising economic, social, and environmental sustainability. However, many of adaptation strategies are not optimal and effective adaptation options. Identifying appropriate and effective or successful adaptation strategies hold paramount importance in establishing a political framework for addressing climate change and avoiding maladaptation (Masud et al., 2017). The reality is that offering a straightforward blueprint for successful adaptation, defining precise measures for its assessment, is a formidable challenge due to the inherently complex and long-term nature of the adaptation process, contingent upon specific circumstances (Schipper, 2020). The complexity of choosing appropriate adaptation options is further compounded by the multitude of goals pursued by policymakers, as noted by Mizina et al. (1999). Policymakers are often tasked with objectives such as maintaining food security, increasing agricultural productivity, promoting exports, and supporting sustainable agriculture and environmental protection. In essence, there exists a range of desirable outcomes that policymakers aim to achieve (Mizina et al., 1999), making the decision-making process among various adaptation options inherently intricate. Making choices among these diverse objectives poses a considerable challenge. Therefore, determining appropriate local adaptation options that are acceptable to stakeholders and adequately meet adaptation requirements is essential (Bhave et al., 2014).

Adaptation planning begins with the identification of options that could prove effective in a local context; however, as time progresses, the imperative arises to determine the preferred options (Smit and Wandel 2006). The planning of adaptation options enables stakeholders to systematically identify and evaluate these options over time. Evaluation becomes a crucial means of determining the most appropriate adaptation option, contributing to the identification of preferred measures (Smit and Wandel, 2006). Given the multitude of potential adaptation options, evaluation helps to prioritize these options (Bhave et al., 2014). The significance of monitoring and evaluating adaptation to climate change is grounded in social, financial, and learning needs. For example, it involves assessing whether adaptation schemes effectively reduce vulnerability and risk and if the invested resources are utilized judiciously (Dinshaw et al., 2014; Scott, 2018). There is thus a need in evaluating the suitability of adaptation options by considering climate change responses in the context of indigenous scientific methods and knowledge (Bhave et al., 2014). Furthermore, evaluating adaptation options should involve determining which strategy deserves promotion, extension, or implementation as the best or highest priority option (Smit and Wandel, 2006). This evaluation process provides an overall assessment of the alternative adaptation options. Even if only ranking and scoring are achieved, it allows for gaining insights into various aspects of the value associated with the adaptation options (Dolan et al., 2001). Additionally, ranking measures play a crucial role in ensuring that the most effective actions take precedence in evaluation or implementation. This approach prevents overlooking superior options in favor of counterproductive or less beneficial ones, especially in resources-scare environment (Acharjee et al., 2020).

Adaptation assessments can act as an input to national adaptation strategies or focus on specific areas such as the water sector (de Bruin et al., 2009). Evaluating adaptation options also helps agricultural decision-makers (producers, agricultural traders, governments) decide whether to pursue adaptation and to choose the best adaptation options (De Loë and Kreutzwiser, 2000).

Developing countries, including Iran, often face limited financial resources for adaptation and the selection of related measures and their ranking for implementation are vital processes if further access is to be gained to invest in instruments and decision-makers at the governmental and non-governmental levels. Such countries need a tool for selecting and prioritizing adaptation measures that can incorporate the financial resources and socioeconomic conditions of individuals (Guillén Bolaños et al., 2018). Adaptation assessment is the identification of specific strategies, policies, and actions that can help reduce current and future vulnerabilities to climate change and also provide the necessary resources (finance, technology, and human capital) to implement them (Ebi and Burton, 2008). Mitigation of greenhouse gas emissions can be measured to assess the effectiveness of policy initiatives but there are no "off-the-shelf" metrics for adaptation (Araos et al., 2016).

Despite the importance of assessing adaptation, two important knowledge gaps are manifest in the literature. First, although, extensive studies have focused on the adaptation of agriculture to climate change, but few have offered critical insights into effective adaptation strategies (Di Falco et al., 2012). Instead, most studies focus on explaining perceived or predicted adaptation behaviors of farmers, with little focus on best adaptation practices at the farm level. Second, sustainability issues are not considered in the design and implementation of adaptation measures. The purpose of this study is to reduce these knowledge gaps by evaluating adaptation options in different parts of the agricultural sector of Iran. This study aims to provide a feasible methodology for identifying successful adaptation measures. "Successful" means adaptation options that do the least harm to farmers and the sector itself and are fully adapted to regional conditions. On the other hand, participation of experts/stakeholders is a prerequisite for adaptation assessment. The evaluation of adaptation options in this study would be incomplete without their technical and economic evaluations (Acharjee et al., 2020). Nigussie et al. (2018), argues that they may know more than farmers about the potential for adapting agricultural practices. Experts are familiar with more types of adaptation because of their specialized education and knowledge, their connection with modern scientific disciplines and work experiences, and their technical and economic knowledge. They have more knowledge about the strengths and weaknesses of each adaptation measure and are thus the best able to evaluate farm-level adaptation measures. The long-term effects of climate change and water scarcity are projected to be significant in countries like Iran (Yazdanpanah et al., 2023b; Nasiri et al., 2024; Shahangian et al., 2021a, 2021b, 2024) and will require successful adaptation, but there is little stakeholder assessment and dialogue in the course of the climate change adaptation process. Therefore, the perspective of agricultural experts has been used to evaluate adaptation options in this study.

1.1. *Conceptualization of successful adaptation evaluation*

Competent evaluation can demonstrate the superiority or the benefits of various adaptation options (De Loë and Kreutzwiser, 2000). Evaluation in the context of adaptation is a process that systematically and objectively determines the relationship, efficiency, effectiveness, and impact of an adaptation strategy to achieve its goals. Evaluation (as opposed to monitoring, which takes place only during the implementation of the action) can be carried out during implementation (known as ongoing evaluation), after the completion of a project (final evaluation) or a few years after the completion of the project (post-implementation evaluation) (Lim et al., 2005). Evaluations assess the suitability, appropriateness, usefulness, or appropriateness of potential adaptation strategies or measures (De Loë and Kreutzwiser, 2000). Adaptation evaluation means evaluating the value of an option based on the specific desirable characteristics of that adaptation action (Smit and Pilifosova, 2003). Approaches to the assessment of adaptation measures are divided into four types: (natural) hazards-based, vulnerability-based, policy-based, and adaptive capacity-based (Lim et al., 2005). In particular, the vulnerability-based approach is useful for assessing the effectiveness of a particular intervention, especially in areas where resources such as data, expertise, time and money are limited (Füssel 2007; Acharjee et al., 2020). This approach places its starting emphasis on the socio-economic dimensions of climate-related risks. In the vulnerability-based approach, the project centers on the delineating the vulnerability of a priority system and evaluating the probability of surpassing critical thresholds of vulnerability in the face of climate change (Lim et al., 2005). This approach begins with past experience in managing recent climate risks. Thus, stakeholders in this approach are directly involved in evaluating adaptation options (Füssel 2007). The main approach in this study, based on vulnerability and adaptation assessment, was conceptualized through an examination of the effectiveness of adaptation measures in terms of their feasibility and acceptability, their harm-reduction potential, and the extent to which they reduce greenhouse gas emissions.

1.2. Evaluation methods of adaptation options

The assessment of adaptation options, as delineated by the frameworks established by the International Panel on Climate Change (IPCC), reveals a variety of methodologies available for evaluation. Among these, benefit-cost (or cost-benefit), cost-effectiveness, and Multi-Criteria Decision-Making (MCDM) analysis emerge as the most prevalent (UNFCCC, 2011). While benefit-cost and cost-effectiveness analyses are often lauded for their effectiveness in performance evaluation, they suffer from limitations, including the inability to comprehensively capture all costs and benefits and restricted stakeholder involvement in prioritizing adaptation options (Champalle et al., 2015). For instance, assigning monetary value to attributes such as environmental conservation poses a significant challenge due to the absence of market trading for environmental benefits (Mizina et al., 1999). However, MCDM circumvents this limitation by accommodating non-monetary attributes and indicators, thereby enabling the evaluation of significant environmental and social impacts of adaptation (Guillén Bolaños et al., 2018). Furthermore, unlike other methods, MCDM incorporates stakeholders' perspectives on evaluation criteria, ensuring a comprehensive assessment of all options, thereby consolidating insights from experts across various domains (Ashofteh and Dougaheh, 2024). In addition, complex decision-making in adaptation necessitates the integration of multiple methodologies and tools. MCDM techniques provide a structured approach to this complexity, facilitating the amalgamation of qualitative and quantitative information, particularly in scenarios with diverse and incomplete databases (USAID, 2013). Hence, MCDMs, characterized by a structured framework, systematically weigh the positive and negative aspects of projects, and fostering interactions among experts (Eslami et al., 2021). In general, multi-criteria decision analysis, which is based on decision matrices and provides structured methods for combining stakeholder views and ranking/prioritizing them, provides better techniques for comparing and supporting the various alternatives involved.

Various Multi-Criteria Decision-Making (MCDM) methods have been utilized in water systems. For instance, AHP, TOPSIS, VIKOR, TODIM, FOWA, and weighted aggregated sum product assessment methods have been developed for various purposes such as water allocation for climate change adaptation, wastewater reuse allocation alternatives, ranking alternatives for river-water transfer, and determining the best game theory method for allocating water from dam reservoirs to agricultural and environmental stakeholders (Golfam et al., 2019a, 2019b, 2021; Azbari et al., 2021, 2022; Ebrahimzadeh Azbari et al., 2024; Ashofteh et al., 2020, 2023). Specific examples include the use of AHP for analyzing adaptation by the farming community (Dutta et al., 2020; Ndamani and Watanabe, 2017), PROMETHEE II for prioritizing adaptation practices in soil and water management (Nigussie et al., 2018), and methods such as. The contribution of the current study lies in the utilization of Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and Graphical Analysis for Interactive Assistance (GAIA) to consider various criteria. The purpose of employing these methods is to select the optimal adaptation strategies from more than thirty alternatives, aiming to minimize the adverse effects of water scarcity and evaluate adaptation strategies in both multi and uni-criterion manners.

1.3. Criteria for successful adaptation evaluation

According to Dolan et al. (2001), the initial step in any evaluation method is identifying criteria. When selecting criteria, it's essential that they are clear, comprehensive (to encompass all decision-making aspects), non-redundant (to prevent double counting), verifiable, directly pertinent to the problem, and analyzable in small units (Guillén Bolaños et al., 2018). A review of literature in MCDM studies reveals the utilization of various criteria across different areas of adaptation, as outlined in Table 1.

Table 1
Review of adaptation evaluation studies and applied criteria.

Sources	Criteria
Dolan et al. (2001)	Effectiveness, economic efficiency, flexibility, organizational alignment, feasibility by the farmer and independent benefits
UNFCCC (2011)	Efficiency, effectiveness, equity, urgency, flexibility, robustness, legitimacy, synergy/coherence
Adger et al. (2005)	Cost-effectiveness, efficiency, the distribution of benefits, *equity* and legitimacy
Leavy et al. (2008)	Effectiveness in achieving goals, flexibility, fairness and equity, efficiency (cost-effectiveness)
Debels et al. (2009)	Usefulness of adaptation measures from achieving goals, implementation time, total cost, strength and flexibility, independence, stakeholder contribution, continuity in time, level of resistance, target population participation, attention to most vulnerable groups, level of environmental protection. Reproducibility and integration of local/traditional knowledge
de França Doria et al. (2009)	Sustainability, global and intergenerational justice, and compliance with cultural norms and social values
de Bruin et al. (2009)	Importance, urgency, no regret; cost–benefit
Sanahuja (2011)	Effectiveness, flexibility, equality and justice (across sectors, regions and communities), efficiency. and sustainability
Teshome et al., 2014	Ecological criteria (effectiveness in reducing erosion, increasing soil fertility and improving water efficiency), economic criteria (costs and benefits), social criteria (social benefits)
Miller and Belton (2014)	General financial needs (reduction of technology and other costs), executive needs (ease of implementation, according to the required time for political intervention), climatic factors (reduction of greenhouse gas and carbon emissions, increased resilience to climate change), economic (stimulating private investment, improving economic performance, creating jobs, contributing to tax sustainability), environmental (protecting environmental resources, protecting biodiversity, supporting ecosystem services), social (reducing inequality, improving health, preserving cultural heritage, poverty reduction), political and institutional (role in political consolidation, improving governance)
Mandryk et al. (2014)	Maximizing farm economic outcomes, maximizing soil quality, minimizing working hours, minimizing nitrogen balance, minimizing hazards.
Michailidou et al. (2016)	Environmental benefits, applicability, cost and social acceptance
Varela-Ortega et al. (2016)	Feasibility of legal and political implementation, employment creation capacity, financial feasibility, increase of farm income, speed of implementation and protection of environmental resources.
Nigussie et al. (2018)	Applicability, affordability, agro-ecosystem, importance, relevance, urgency, no regret, co-benefits to other sectors, mitigation, agro-ecosystem feasibility, technical feasibility, Institutional Feasibility, socioeconomic feasibility,
Maes et al. (2019)	feasibility (technical, knowledge, power), acceptance (social, religious, traditional, livelihood), cost (implementation, maintenance), effectiveness (short-term, long-term).
Acharjee et al. (2020)	Importance, urgency, no-regret, co-benefits, technical complexity, social complexity, and institutional complexity

2. Materials and methods

2.1. Measuring instrument

In this study, the PROMETHEE GAIA plane was used to analyze and prioritize adaptation methods. A multi-criteria questionnaire was used to collect data. PROMETHEE is an open-source systems monitoring and alerting toolkit, and GAIA reveals key aspects of the decision-making problem, helping the decision-maker to make choices and finalize their decision. The multi-criteria questionnaire included a matrix of adaptation options including six options for crop management, seven for farm management and 20 for water management to adapt to water scarcity, plus nine research criteria. After PROMETHEE was run, the adaptation options in each of the dimensions of crop, farm, and water management were ranked separately and the most appropriate adaptation options in each of these dimensions were determined.

2.2. Participants

The present study was conducted in Ahvaz city, in the center of Khuzestan province in southwestern Iran using a sample of ten agricultural experts from the two large agricultural centers from the Agricultural Jihad Organization (Ahvaz and Khuzestan Agricultural Jihad Organizations).

Respondents were purposively selected using the expert sampling technique. Some of the criteria for appointing agricultural experts included mastery of water scarcity issues in agriculture, familiarity with various adaptation methods (having published articles in this field), and work experience as an agricultural expert for at least five years. Finally, two experts in agricultural sciences with a master's degree, three experts in agricultural extension and education with a doctoral degree, three experts in water sciences with a doctoral degree, two experts in agronomy and plant breeding with a doctoral degree were selected. The average age of the agricultural experts was 45 years and their average work experience was 12.5 years.

2.3. PROMETHEE methodology: steps of multi-criteria analysis

The PROMETHEE methodology consists of five main steps outlined below.

2.3.1. Identifying adaptation options (measures/actions)

The initial phase of conducting a multi-criteria analysis involves identifying adaptation options. This data can be gathered through literature reviews, interviews, and workshops involving diverse stakeholders and key actors (Guillén Bolaños et al., 2018). In a preliminary study, adaptation strategies to address water scarcity in the study area were identified through observations, interviews, and literature reviews (See Zobeidi et al., 2022). These strategies were categorized into three groups based on their type and primary focus: crop, farm, and water management. Table 2 presents the research list of adaptation measures along with their respective codes.

2.3.2. Selection of criteria for analysis

In the second step, eight criteria for evaluating successful adaptation were selected, including effectiveness (importance), affordability, technical feasibility, institutional feasibility, social feasibility, flexibility, traditional acceptance, and environmental side effects.

2.3.2.1. Effectiveness. Effectiveness or importance describes how well effective an adaptation option can mitigate climate damage. It signifies the necessity of implementing an option to alleviate the adverse effects of climate change, potentially reducing significant harms associated with it. In essence, an effective option yields considerable benefits in terms of avoided consequences, albeit potentially at a high cost (de Bruin et al., 2009). Effectiveness is also linked to an adaptation action's ability to accomplish its intended objectives. It can be assessed by either i) mitigating the effects and minimizing exposure, or ii) mitigating risks, avoiding hazards, and enhancing safety (Adger et al., 2005). However, defining adaptation solely in terms of its effectiveness in achieving goals is insufficient for two reasons. Firstly, an action may be successful in terms of a stated goal but result in additional external effects at other spatial scales. What may appear successful in the short term may not be as effective in the long term. Secondly, an action that proves effective for one entity may generate negative externalities and potentially impact other adaptive capacities. Hence, besides effectiveness, other criteria must be considered.

Table 2
Adaptation measures.

	Crop management		Water management		Farm management
A1	Cultivation of crops with short or long yielding	B1	Use pipes to transfer water around the farm	C1	Pest and disease management
A2	Cultivation hybrid seeds and genetically modified seeds	B2	Changing irrigation time	C2	Reduce the space between crop rows
A3	Cultivation of salinity-resistant seeds	B3	Use modern irrigation	C3	Garden cropping pattern
A4	Relay intercropping	B4	Use of unconventional water sources	C4	Mulching
A5	Mixed intercropping	B5	Use a combination of salt and fresh water	C5	No summer planting of high-water-consuming crops.
A6	Change type of crop	B6	Lining canals or using nylon cover for canal soil floor	C6	Replacement of irrigated cultivation with rainfed
		B7	Increasing the time intervals between irrigations	C7	Change of cultivation method (drying or seedling cultivation)
				C8	Diversify farm activities
				C9	Decreasing area under cultivation
				C10	Change plot size—reduce the length and width of the plot
				C11	Low tillage/no tillage method
				C12	Summer plowing
				C13	Using organic fertilizers
				C14	Runoff collection and control
				C15	Change the date of cultivation
				C16	Crop rotation
				C17	Good maintenance of canals and drainage
				C18	Weed control
				C19	Land degradation
				C20	Tree planting around the farms

2.3.2.2. Affordability. Economic efficiency, commonly referred to as cost-benefit analysis, plays a crucial role in evaluating adaptation options. Optimal levels of adaptation in terms of economic efficiency are defined as those levels at which adaptation and residual damage costs are minimized and deemed affordable. It is essential that the costs of implementing an adaptation measure are lower than the costs of the potential harm it aims to prevent (Dolan et al., 2001). Similarly, at the farm level, an adaptation option is preferable if it is economically viable or offers economic advantages that outweigh its costs. Perceptions of affordability can significantly influence the acceptance of adaptation measures, regardless of their profitability based on economic statistics (Dolan et al., 2001).

2.3.2.3. Technical feasibility. Feasibility encompasses the assessment of the practicality and desirability of climate goals and response options (Williams et al., 2021). Technical feasibility, focuses on evaluating the technological expertise and the availability of necessary human, financial, and administrative resources for a specific option (Singh et al., 2020). It is crucial to note the importance of technical feasibility in agricultural adaptation, where the complexity of innovations often poses significant challenges in the technology transfer process (Dolan et al., 2001). Technical challenges inevitably arise during the planning and implementation of adaptation strategies, which may include difficulties arising from a lack of technical expertise or inadequate instrumentation for option implementation. Addressing these technical hurdles is paramount for the successful execution of agricultural adaptation measures.

2.3.2.4. Institutional feasibility. Institutional feasibility refers to institutional and legal capacity (Singh et al., 2020). The preferred adaptation option is one that aligns with laws, regulations, and institutional structures. Dolan et al. (2001) evaluated this criterion as organizational adaptation. Adaptations compatible with existing organizational structures and the prevailing legal system are more likely to be accepted than those requiring changes to existing structures (Acharjee et al., 2020). The presence of formal procedures, bureaucratic structures, procedural regulations, and other institutional actions tends to increase when adaptations affect longstanding organizational structures and functions. Additionally, cooperation among different institutional areas increases, which may generate tension with existing practices and structures. In the agricultural sector, for example, the implementation of an irrigation system or diversification of farm operations is more desirable if there are institutional structures to assist in implementation and facilitate acceptance, without leading to conflicts in other areas of agriculture (Dolan et al., 2001).

2.3.2.5. Social feasibility. Social feasibility involves assessing the sociocultural acceptability of the option concerning local norms, values, and beliefs. This entails evaluating whether the proposed adaptation aligns with existing social practices and customs, and whether it is likely to be embraced by the affected community or population (Singh et al., 2020).

2.3.2.6. Flexibility. Flexibility refers to the ability to change behavior in response to changing conditions (Debels et al., 2009; Altvater et al., 2012). It entails the capability of a system to swiftly recover performance after a malfunction. Given the inherent uncertainty of climate change, flexibility becomes a desirable attribute of adaptation policies (Miller and Belton, 2014). Flexible adaptation options not only mitigate vulnerability to diverse climate change risks but also function effectively across a broad spectrum of climatic conditions rather than being optimized for specific predicted scenarios. For instance, a management strategy like crop selection that mitigates risks across a wide range of humidity and temperature conditions exhibits greater flexibility than a product exclusively produced under narrow conditions, vulnerable to external variations (Dolan et al., 2001).

2.3.2.7. Traditional acceptance. Attention to integrating local and traditional knowledge in the design or implementation of adaptation measures is important when examining the acceptability of adaptation methods, Traditional acceptance refers to the degree of acceptability of an adaptation strategy aligning with the context of traditional values (Maes et al., 2019).

2.3.2.8. Environmental side effects. Side effects typically encompass both desirable and undesirable outcomes (Altvater et al., 2012). An adaptation option may yield environmental benefits, such as safeguarding environmental resources, biodiversity, and ecosystem services. Addressing the greenhouse effect can also be seen as an environmental impact. Consequently, in the current study, each option is evaluated based on its effects on environmental benefits. For instance, some adaptation measures mitigate greenhouse gas emissions, thereby aligning with mitigation policies. Conversely, other measures may yield adverse effects, such as increased greenhouse gas emissions (de Bruin et al., 2009).

2.3.3. Weighting the criteria

In cases where certain criteria hold more importance than others and are given higher priority, these criteria can be assigned different weights based on their relative significance (UNFCCC, 2011). Significance coefficients indicate the influence of the criteria. The criteria are presented in a sequential manner and represent non-compensatory methods. They demonstrate the influence of criteria in establishing a ranking and are independent of the measurement scale of the criteria (Figueira et al., 2005). In this stage, the criteria were weighted. In this study, to ascertain the weight of each criterion, an AHP questionnaire was formulated and distributed to six agricultural experts. The results of the criteria weighting are depicted in Table 3.

2.3.4. Determining the score of each option based on each criterion

The performance of each adaptation option was scored in relation to each criterion in step 4. All options were scored using a five-point Likert scale, ranging from very low (1) to very high desirability (5).

2.3.5. Conclusion and interpretation of results (ranking)

In this fifth step the total score for each option was calculated by multiplying the standardized scores by their weight. Finally, the adjusted weight scores were added together and compared. The main result of a multi-criteria analysis is to rank the adaptation options and identify the strengths and weaknesses of each one (UNFCCC, 2011).

2.4. Data analysis

Data analysis employed the PROMETHEE and GAIA plane methods, facilitated by the Visual PROMETHEE software. PROMETHEE methods are part of multi-criteria analysis and were developed by Brans in the early 1980s. The PROMETHEE method was deemed suitable for this

Table 3
Weights of relative importance.

Criteria	Actual weight (percent)	Weight stability intervals (percent)		
		Crop management	Farm management	Water management
Effectiveness-importance	15	0–29.49	11.36–15.22	11.27–15.21
Affordability	16	8.95–25.52	14.44–16.18	0–19.39
Institutional feasibility	13	0–42.46	11.61–13.97	12.96–59.74
Technical feasibility	11	0–21.87	9.20–11.38	10.95–100
Social feasibility	10	0–100	9.70–11.79	0–10.18
Traditional acceptance	16	10.07–22.75	15.87–18.09	0–16.42
Flexibility	10	0–22.71	9.39–16.24	3.23–10.03
Environment side effects	9	0–13.82	6.54–10.30	8.85–16.75

study for several reasons. Firstly, PROMETHEE methods boast extensive software support for data management, particularly in terms of display and comparing scenarios, as well as visualizing the effects of different weights, criteria, and preferential functions. The method provides information that is easily comprehensible for decision-makers and analysts (Brans and De Smet, 2016). Secondly, the PROMETHEE approach initiates with a comprehensive overview of multi-criteria problems and underscores that these problems cannot be resolved without additional insights into decision-makers' preferences (Brans and De Smet, 2016). Thirdly, in practical terms, the PROMETHEE method is much simpler compared to other multi-criteria analyses such as AHP. PROMETHEE questionnaires are more concise and condensed than the extensive and intricate AHP questionnaires. Furthermore, PROMETHEE does not assess consistency rates, resulting in a very low likelihood of the findings being deemed unacceptable post-analysis. Nevertheless, the AHP technique was employed in conjunction with PROMETHEE solely for the purpose of weighting the criteria, based on pairwise comparisons of criteria.

In the PROMETHEE method, A represents a set of options available for selection. Assuming that K is the decisive criterion for each option, a_j represents the value of criterion J for option a. The ranking process is conducted in three steps using this methodology.

Step 1: Determining the preference function for each of the J criteria (Pj): the PROMETHEE method has six types of preferential function. The "usual" function is used for all criteria. This type of preferential function is usually used when items are measured on a Likert scale.
Step 2: A weight is assigned to each of the criteria based on the importance of the criterion (Wj) after the preferential function is determined. The weights entered are normalized by Visual PROMETHEE software and the total will be 100.
Step 3: After performing pairwise comparisons and selecting one of the appropriate functions for the priority or preference function, the final ranking or prioritization of the options is obtained by summing the priority of all indicators to produce the total value, obtained using the formula in Equation (1) PROMETHEE including PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking).

Equation (1)

$$\pi(a,b) = \sum\nolimits_{j=1}^{k} \mathrm{wj}\ \mathrm{pj}(a,b),\ \left[\sum\nolimits_{j=1}^{k} \mathrm{wj} = 1\right]$$

In Equation (1) wj (j = 1,2, …, n) represents the normalized weight of each criterion. The value of π (a, b) varies between zero and one. When this value is higher, the priority of option a over b is shown in all indicators. The priority of option a over option b is denoted by π(a, b). At this point two parameters, leaving and entering outranking flows, must be calculated to the respective outranking power and weaknesses of each alternative over the other (Cinelli et al., 2014).

In partial ranking used to calculate the power of the general preference of option a over other options, the *positive (*leaving) *outranking flow* is calculated using the formula in Equation (2). This flow denotes how much priority option a exceeds the other options. This flow is the power of option a and the largest Φ + (a) indicates the best option. Equation (3) calculates the preference of other options over option a, the *entering* flow. This flow indicates the priority of the other options over option a. The smallest Φ- (a) indicates the best option.

Equation (2) the positive (leaving) *outranking flow:*

$$\varphi^{+}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(a,x)$$

Equation (3) the negative (entering) outranking flow:

$$\varphi^{-}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(x,a)$$

The PROMETHEE II total preorder is obtained by considering the net flow, which is calculated as the difference between positive outranking and negative outranking (Equation 4).

Equation (4)

$$\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a)$$

The GAIA plane is a descriptive complement to the PROMETHEE method and is an intuitive interactive module based on principal component analysis. The GAIA plane provides the decision-maker with a visual representation of a combination of key features of the decision problem, such as the synergies and contrasts among preferential measures or selections (Mareschal, 2013).

2.5. *Assessment of uncertainty sensitivity analyses*

Sensitivity analysis should be calculated in two stages: weighting the criteria and evaluating the performance of the options (i.e., scoring) (Buchholz et al., 2009). In the Analytic Hierarchy Process (AHP), the inconsistency index serves as an indirect indicator of uncertainty during the weighting phase. The use of the inconsistency coefficient reveals the relative confidence apparent in the findings. In the analysis, the inconsistency index coefficient at this stage was approximately 0.70, falling within the acceptable threshold (below 0.1). Using sensitivity analysis to determine weight stability intervals is an effective method for assessing uncertainty. These intervals represent the range of values that the weight of one criterion can take without altering the results generated by the initial set of weights, provided that all other weights remain constant (Mareschal, 1988).

The weights applied (actual weight) for all criteria fell within the stability intervals range, ensuring that the prioritization results remain unchanged even as weights are adjusted (Table 3). To bolster the results and foster consensus in the participatory process, we adopt the approach outlined by Champalle et al. (2015), which involves conducting a sensitivity analysis by re-evaluating the MCDM.

This analysis entails adjusting the weight of one of the eight criteria based on the local context to observe variations in the total score of each option. Given the participatory nature of our research framework, stakeholders may adjust weights according to their preferences during the prioritization process. Stakeholders, collectively, have the liberty to make arbitrary weight adjustments and conduct sensitivity analyses at least twice using different weights.

To streamline the sensitivity analysis process, end users can utilize the same multivariate matrix, modify specific criterion weights, and observe changes in MCDM scores and their impacts on interactions. Results indicate that priorities remain consistent even after two rounds of weight adjustments.

3. Results

Table 4 shows the descriptive characteristics of adaptation measures based on evaluation criteria. The efficacy criterion displayed the highest values across all three categories of adaptation measures, including crop management (M = 4.38; SD = 0.84), farm management (M = 4.11; SD = 0.91) and water management (M = 3.87; SD = 1.08).

Table 5 displays the prioritization of adaptation options for crop, water, and farm management. Among the crop management measures, alternatives A4 (relay intercropping), A6 (change of crop type), and A5 (mixed intercropping) rank highest based on net flow. These options entail minimal changes in the field, allowing farmers to select adaptable crops and identify low-risk options. Following these, the cultivation of salinity and drought-resistant crops is significant. Measures A2 and A1 involving hybrid or genetically modified seeds, and crops with short or long yield periods resulting in negative outcomes, are not recommended. Regarding water management, options B6, B1, and B7 rank highest with a positive net flow. These include lining earthen canals and employing nylon covers for canal floors, piping water to fields, and

Table 4
Descriptive characteristics of adaptation measures.

	Effectiveness	Affordability	Institutional feasibility	Technical feasibility	Social feasibility	Traditional acceptance	flexibility	Environmental side effect
Crop management								
Average	4.38	4.20	3.23	3.32	3.95	3.20	3.65	3.20
Standard dev	0.84	0.77	0.64	0.97	0.96	0.85	0.63	0.65
Farm management								
Average	4.11	3.85	3.35	3.31	3.20	3.17	3.15	3.28
Standard dev	0.91	0.92	0.79	0.86	1.25	0.80	0.80	0.65
Water management								
Average	3.87	3.70	3.30	3.29	3.16	3.20	3.27	3.19
Standard dev	1.08	1.10	0.87	0.61	1.09	0.69	0.79	0.64

Table 5
PROMETHEE II results—outranking adaptation measures.

Rank	Crop management				Water management				Farm management			
		φ	φ+	φ-		φ	φ+	φ-		φ	φ+	φ-
1	A4	0.1017	0.2975	0.1958	B6	0.3403	0.4590	0.1187	C1	0.3350	0.4791	0.1441
2	A6	0.0710	0.3007	0.2297	B1	0.3402	0.5362	0.1960	C18	0.2723	0.4578	0.1855
3	A5	0.0447	0.2831	0.2383	B7	0.1085	0.3293	0.2208	C16	0.2485	0.4212	0.1727
4	A3	0.0118	0.3219	0.3101	B5	−0.1202	0.1808	0.3010	C20	0.2449	0.4284	0.1835
5	A2	−0.0662	0.2705	0.3367	B3	−0.497	0.1932	0.3428	C17	0.2134	0.4285	0.2150
6	A1	−0.1631	0.1897	0.3527	B2	−0.1532	0.1773	0.3305	C19	0.1798	0.4266	0.2469
7					B4	−0.3660	0.1143	0.4803	C7	0.0940	0.3630	0.2690
8									C6	0.0455	0.3462	0.3007
9									C14	0.0345	0.2890	0.2545
10									C2	0.0156	0.3074	0.2918
11									C13	−0.0006	0.2666	0.2672
12									C9	−0.0995	0.2507	0.3502
13									C3	−0.1229	0.2357	0.3587
14									C4	−0.1234	0.2396	0.3630
15									C11	−0.1681	0.1958	0.3639
16									C8	−0.1738	0.2192	0.3930
17									C5	−0.2174	0.1951	0.4125
18									C15	−0.2310	0.1807	0.4117
19									C12	−0.2377	0.1653	0.4029
20									C10	−0.3092	0.1432	0.4574

adjusting irrigation intervals to combat water scarcity, respectively. These measures take precedence over others.

In farm management, the top three priority options based on higher net benefits are C1 (pest and disease management), C18 (weed control), and C16 (crop rotation). Subsequently, options C20, C17, C19, C7, C6, C14, and C2 warrant attention and investment. However, methods with negative effects are excluded from the agricultural extension program because their chances of success are minimal.

The diamond network views (Figs. 1–3) show adaptation options for crop, farm and water management with the greatest negative and positive values. This network is based on the relative position of adaptation measures. The display used in the diamond network makes it very easy to understand the proximity between actions. This network view can be used to determine how alternative adaptation options are ranked based on both positive and negative trends and the order in which they can be performed from the most to the least desirable.

Fig. 4 illustrates the GAIA plane for crop management options. According to Mareschal (2013), a value near 70% indicates the validity of the GAIA plane's conclusions. The quality of the GAIA plane for crop management was 76.5%, affirming the validity of the findings. Options exhibit greater favorability towards proximate criteria and less favorability towards divergent criteria.

Criterion A6 (changing the type of crop) closely aligns with institutional and social feasibility, suggesting its easy adaptation in these aspects. However, A6 shows less alignment with the criterion of environmental effects, indicating limited environmental benefits as

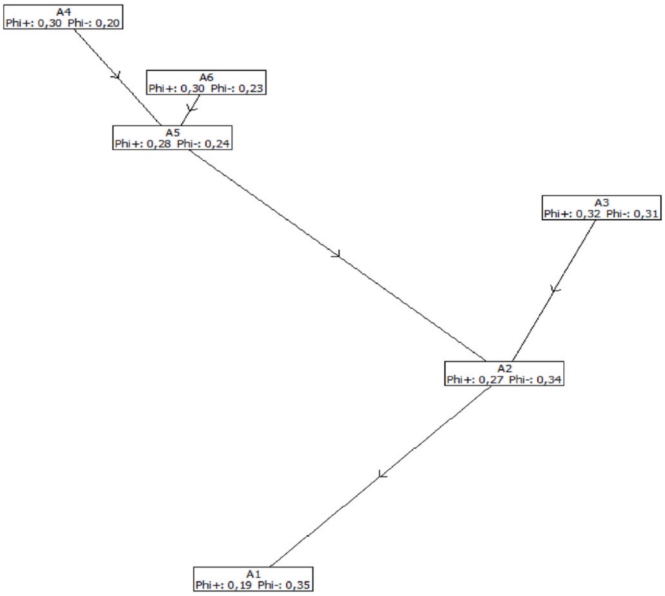

Fig. 1. Diamond PROMETHEE network view of crop management options.

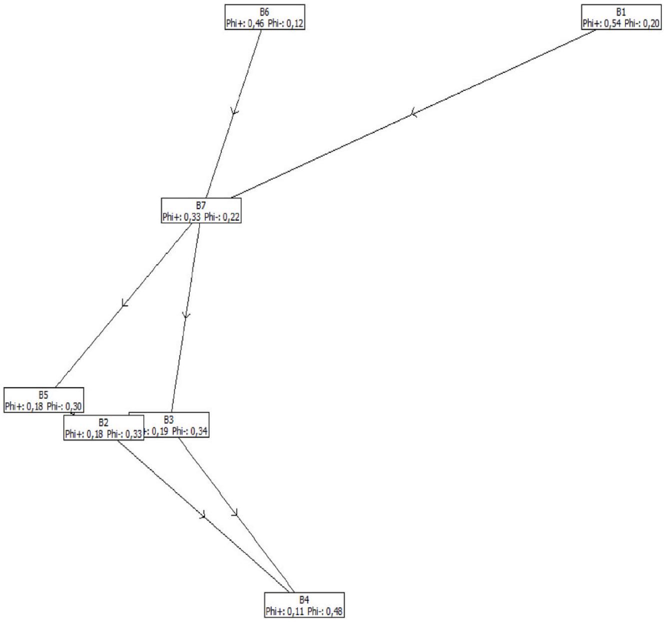

Fig. 2. Diamond PROMETHEE network view of water management options.

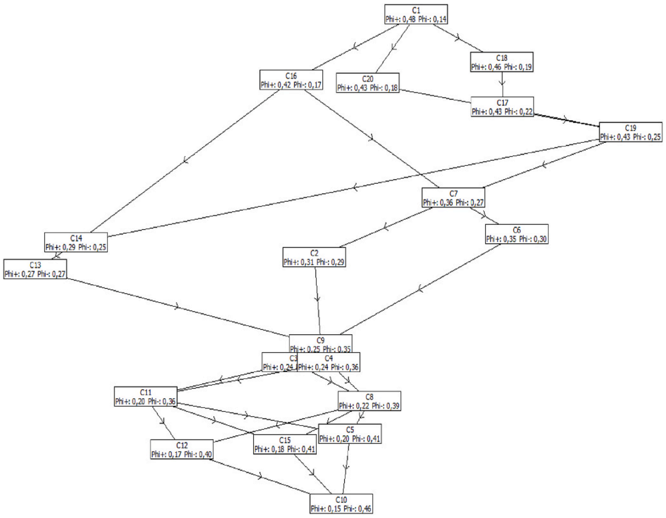

Fig. 3. Diamond PROMETHEE network view of farm management options.

evidenced by its lower score.

Option A5 (mixed intercropping) is more aligned with the traditional acceptance criterion compared to other criteria, implying its potential as a traditional method, particularly in promoting crops suited to water scarcity.

Option A4 (relay intercropping) holds a favorable position concerning social feasibility. Conversely, Option A2 aligns more closely with the technical acceptance criterion, receiving a high score in technical acceptance but exhibiting a weak score in traditional acceptance due to its misalignment.

On the contrary Option A2 is closer to the technical acceptance criterion and thus has a high score for technical feasibility but is completely opposite to the traditional acceptance criterion and thus has a very weak score in traditional acceptance. A3 is very strong in terms of environment side effects, but very unfavorable in terms of traditional acceptance.

The decision vector (the thicker/red vector) is a representation of the weighting of the criteria. The direction of the decision vector indicates which criteria align with the PROMETHEE rankings and which do not. In this plane, the decision vector opposite the environmental side effects criteria, suggesting that lower scores in environmental criteria can be anticipated among the top PROMETHEE rankings (such as A6).

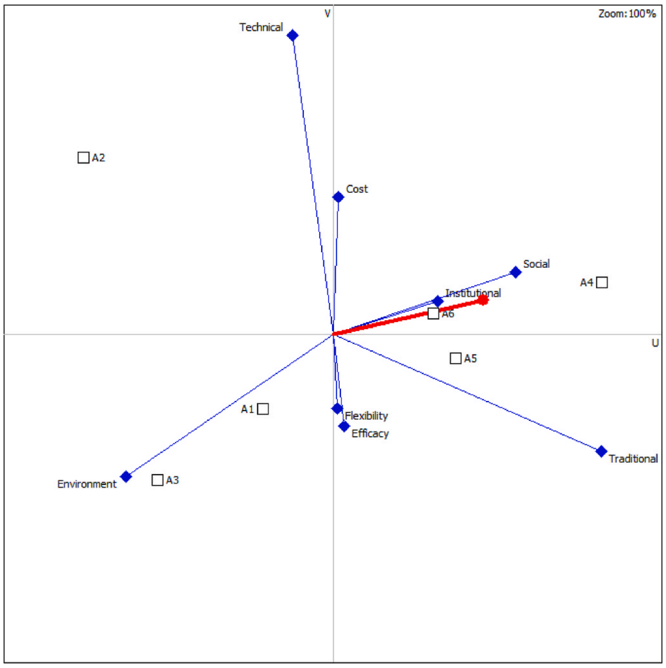

Fig. 4. GAIA analysis of crop management measures (Quality level = 76.5 %).

Table 6 displays the ranking of options based on the net flow of the uni-criterion. Regarding efficacy, raising drought-resistant crops emerged as the most effective option. For affordability and institutional feasibility, changing the type of crop proved to be the most suitable choice. In terms of technical feasibility, both growing hybrid seeds and changing the type of crop were identified as optimal options. When considering traditional acceptance and social feasibility, option A4, relay intercropping, stood out as the best choice, while cultivating salinity or drought-tolerant cultivars appeared to be the most flexible adaptation option.

Fig. 5 depicts the GAIA plane for water management options. The quality of the GAIA plane for water management was 93.8%, indicating very high validity. The B6 adaptation method closely aligns with the decision vector and performs well across all criteria. Meanwhile, the B7 adaptation method occupies a favorable position in terms of affordability (To demonstrate affordability,the term "Cost" was incorporated within the graphical representations of GAIA (Figs. 4, 5 and 6)).

According to the GAIA plane, actions B2, B3, and B5 form a cluster of adaptation methods positioned at the opposite end of the spectrum concerning traditional acceptance, technical feasibility, efficacy, and social feasibility criteria. Action B4 slightly outperforms others from an environmental side perspective.

According to Table 7, concerning efficiency, affordability, traditional acceptance, social feasibility, and flexibility criteria, the action of lining earthen water canals and using nylon coating for the canal floor (B1) holds a more favorable position compared to institutional feasibility, technical feasibility, and environmental side effects criteria.

The quality of the GAIA plane for farm management was 81.8%, demonstrating the validity of the GAIA results. The adaptation methods C7 (change of cultivation method -drying or seedling cultivation) and C19 (land integration) are positioned close to the decision vector and obtained positive scores across all criteria. Only methods aligned with the direction of the decision vector are recommended. Among all the farm management measures, methods 1, 6, 7, 16, 17, 18, 19, and 20 are thus suggested (Fig. 6).

Table 6

Uni-criterion net flow of agricultural adaptation measures- Crop management for each criterion.

	Effectiveness	Affordability	Institutional feasibility	Technical feasibility	Social feasibility	Traditional acceptance	Flexibility	Environmental side effect
A1	−0.0600	−0.2000	−0.1200	−0.2600	−0.2600	−0.1200	−0.2600	−0.800
A2	−0.1200	0.1200	−0.1400	0.4200	−0.2200	−0.5200	−0.0600	0.1800
A3	0.1400	−0.0600	−0.1200	−0.1400	−0.1400	−0.1600	0.2600	0.5000
A4	0.0000	0.0000	0.1400	0.0800	0.3600	0.4200	0.0600	−0.3800
A5	−0.0200	−0.1000	0.0400	0.0400	0.0400	0.3400	0.0600	−0.1200
A6	0.0600	2.400	0.2000	−0.1400	0.2200	0.0400	−0.0600	−0.1000

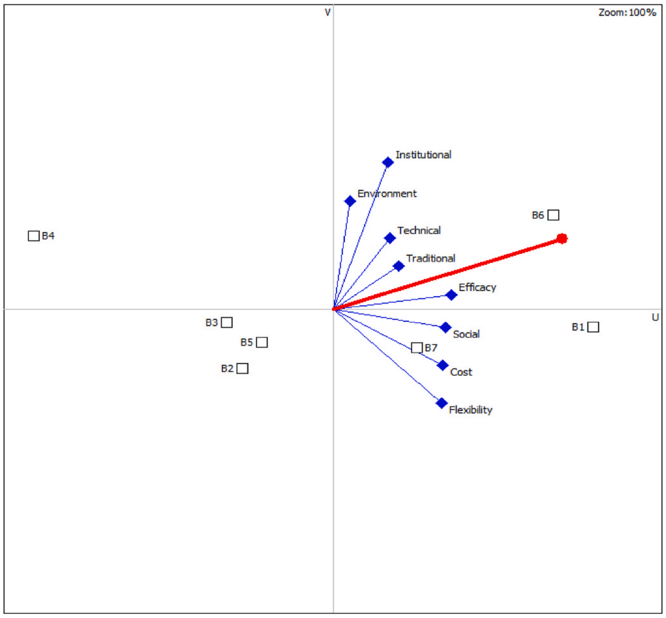

Fig. 5. GAIA analysis of water management measures (Quality level = 93.8 %).

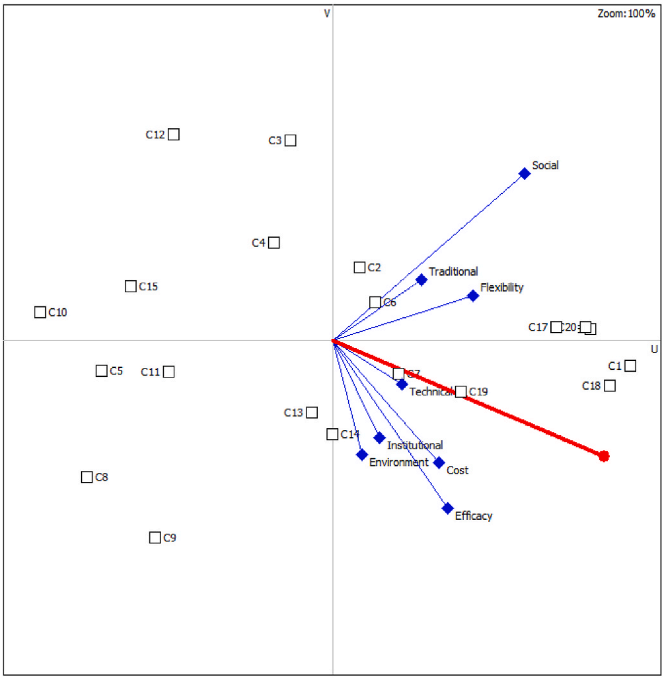

Fig. 6. GAIA analysis of farm management measures (Quality level = 81.8 %).

Adaptation methods C18 (weed control) and C20 (tree planting) emerge as priorities in terms of efficacy (Table 8), with tree planting receiving the highest score for social feasibility. Method C1 (pest and disease management) achieves high scores in affordability and traditional acceptance. C6 (replacing irrigated crops with rainfed ones) stands out as one of the simplest methods in terms of technical feasibility, while C7, (changing the cultivation method via the drying or seedling cultivation method) is deemed a priority in terms of institutional feasibility. Option C19, land integration, proves to be the most appropriate option in terms of environmental side benefits and reducing greenhouse gas emissions.

4. Discussion

Agricultural adaptation efforts, particularly in crop, farm, and water management, play a pivotal role in enhancing resilience and ensuring food security amidst changing environmental conditions. Evaluation of adaptation measures through consultation with agricultural experts facilitates the identification of strengths and weaknesses in various methods, as well as predicts the level of acceptance among farmers. This study employed the PROMETHEE and GAIA methodologies to assess adaptation measures across eight criteria, encompassing effectiveness/importance, affordability, institutional feasibility, technical feasibility, social feasibility, traditional acceptance, flexibility, and environmental side effects.

Findings have revealed valuable insights regarding the prioritization of specific adaptation measures across diverse dimensions of assessment. Notably, certain adaptation measures in crop management, including relay intercropping, change of crop type, and mixed intercropping, have emerged as significant priorities. These findings underscore the high levels of social feasibility and traditional acceptance associated with relay intercropping in the study context. Indeed, relay intercropping, a practice where one crop is sown after the previous one has reached a certain stage of growth, appears to be deeply ingrained in the agricultural traditions of the region. Moreover, our findings reveal substantial traditional acceptance for changing crop types, indicating that while farmers in our region may have limited intention to change crops extensively, they do exhibit a willingness to rotate between two or three familiar crops. This flexibility in crop selection reflects farmers' adaptive capacity in response to changing climate conditions. It demonstrates their openness to experimenting with alternative crops that they are familiar with, which may be better suited to evolving environmental conditions.

Our findings align with existing literature, such as the study by Teshome et al. (2014), which suggests that farmers tend to adhere to methods that are familiar to them. In our study, this notion is corroborated by the observation that two of the top three adaptation methods, namely relay intercropping and mixed intercropping, received higher traditional acceptance scores. Agricultural experts emphasize that the likelihood of success of adaptation strategies is enhanced when they are traditionally accepted by farmers. Moreover, the popularity of relay and mixed intercropping can be attributed to their ability to promote crop diversification, thereby reducing the risk of crop failure associated with mono-cropping practices. By cultivating multiple crops, farmers can hedge against the adverse effects of climate-related hazards, such as

Table 7
Uni-criterion net flow Φk of agricultural adaptation options–water management for each criterion.

	Effectiveness	Affordability	Institutional feasibility	Technical feasibility	Social feasibility	Traditional acceptance	Flexibility	Environmental side effect
B1	0.4833	0.3500	0.1500	0.2000	0.5000	0.3000	0.6167	0.1167
B2	−0.2833	−0.0833	−0.2833	−0.1833	0.0167	−0.1333	−0.1167	−0.1000
B3	−0.2000	−0.1667	−0.1500	−0.0667	−0.2667	−0.2833	−0.0667	0.0500
B4	−0.5333	−0.6500	−0.1000	−0.2167	−0.5833	−0.1833	−0.6500	0.0833
B5	−0.1500	−0.1167	−0.0333	−0.0667	−0.1167	−0.1667	−0.0500	−0.2667
B6	0.4167	0.3500	0.4833	0.3500	0.4167	0.2667	0.1667	0.2167
B7	0.2667	0.3167	−0.0667	−0.0167	0.0333	0.1500	0.1000	−0.1000

Table 8
Uni-criterion net flow Φk of agricultural adaptation options-farm management for each criterion.

	Effectiveness	Affordability	Institutional feasibility	Technical feasibility	Social feasibility	Traditional acceptance	Flexibility	Environmental side effect
C1	0.3842	0.4158	0.1947	0.1632	0.4316	0.4737	0.4474	0.0421
C2	−0.1526	−0.0421	0.0526	0.1947	0.1053	0.1421	0.0526	−0.2316
C3	−0.2895	−0.2632	−0.3105	−0.3316	0.2211	0.2158	0.0158	−0.2000
C4	−0.1368	−0.0842	−0.2737	−0.2368	0.0895	−0.1000	0.0158	−0.1684
C5	−0.3000	−0.4000	−0.1316	0.0053	−0.4789	−0.2737	−0.2789	0.3053
C6	−0.0474	0.0474	0.0526	0.2947	0.1421	0.1211	−0.0737	−0.2263
C7	0.1000	−0.0211	0.2632	0.1105	0.0211	0.0684	0.1842	0.0474
C8	0.0789	−0.2526	0.1947	−0.1053	−0.6895	−0.1211	−0.5737	0.0684
C9	0.0526	0.0737	0.1947	−0.3579	−0.6632	−0.3579	−0.2842	0.1737
C10	−0.4105	−0.3368	0.0737	−0.3316	−0.5211	−0.3368	−0.3421	−0.2684
C11	−0.0789	0.0579	−0.2368	−0.3358	−0.3263	−0.2000	−0.3158	−0.0421
C12	−0.5737	−0.5053	−0.1842	−0.1105	−0.0158	−0.0263	−0.1053	−0.2421
C13	0.1053	0.3000	−0.1526	0.0684	−0.1316	−0.1000	−0.1842	−0.0526
C14	0.2947	0.1842	−0.0421	−0.0158	−0.3000	0.0316	0.0684	−0.1526
C15	−0.4105	−0.2674	−0.2316	−0.0789	−0.3105	−0.2368	−0.1947	0.0053
C16	0.3579	0.2316	0.1842	0.2526	0.5526	0.1526	0.3526	−0.1000
C17	0.1737	0.1474	0.1842	0.2053	0.5526	0.0526	0.3474	0.2105
C18	0.4000	0.2947	0.1842	0.0789	0.5579	−0.0158	0.5053	0.3105
C19	0.0526	0.1421	0.1737	0.1789	0.1632	0.2211	0.1632	0.4211
C20	0.4000	0.2789	−0.0421	0.0737	0.5674	0.2895	0.2632	0.1000

droughts or pest outbreaks, which may disproportionately affect a single crop species.

The greater the diversity within production systems, the more resilient they become in ensuring food security and nutrition amidst climate change. Enhancing crop diversity and resilience to climate change and water scarcity equips farmers to better manage pest outbreaks and minimize the risk of pathogen transmission, which can be exacerbated by climate variability. This, in turn, helps mitigate the impacts of climate stress on crop production (Aryal et al., 2020). Acharjee et al. (2020) underscored in their study that integrated product management emerged as a priority adaptation option in the production management sector. Moreover, increased diversity in agricultural production systems correlates with enhanced food and nutrition security in the face of climate change.

In terms of farm management methods, agricultural experts prioritize pest and disease management, weed control, and crop rotation. This perspective aligns with the findings of a study by Nigussie et al. (2018), which examined the prioritization of adaptation options for land and soil management. Similarly, methods related to crop rotation, composting, and changes in fertilizer use were highly ranked based on various criteria in their study. All three methods of pest and disease management, weed control, and crop rotation demonstrate relatively high efficacy, social feasibility, and flexibility. Furthermore, pest and disease management and weed control methods have a longstanding tradition of use in the region and are considered relatively flexible, making them easily extendable and socially accepted.

These findings suggest that the approaches employed are effective in controlling pests and diseases, are culturally acceptable within the local community, and can be readily adapted or modified to suit the specific needs of the region.

Among crop management measures relay intercropping has the highest rank, but it has the lowest score in positive environmental side effects. There appears to be a discrepancy between the effectiveness of intercropping as a crop management strategy and its environmental impact. Similar trends were observed for crop rotation in the context study. While rotating crops ranked second among farm management measures across all criteria, it received a significantly lower ranking (13th) in terms of environmental side effects. This highlights the potential for conflicting evaluation criteria in prioritizing adaptation options, underscoring the need for stakeholders and decision-makers to clarify the importance of each criterion in the decision-making process. In addition, the study suggests that while changing the type of crop may be technically complex, the social or organizational complexities associated with implementation may be relatively lower. This insight provides valuable context for understanding the challenges associated with implementing adaptation measures in a dry region. It emphasizes the need for tailored strategies that account for the specific technical, social, and organizational complexities inherent in each measure. The comparison with Acharjee et al. (2020), which found that social complexity outweighed technical or organizational complexities for crop management measures, adds another layer of understanding to the challenges faced in the context area.

The top three priorities in water management to address water shortages are: 1) canals lining or using nylon covers in canals, 2) utilizing pipes for water transfer to crops, and 3) extending the time between irrigations. According net preference flow, these methods are highly preferred. In a study by Nigussie et al. (2018), river diversion, leaching and erosion prevention, and drip irrigation were identified as the top three adaptation options on a larger scale. Paudel and Kafle (2012) focused on community soil and water conservation, highlighting the importance of protection ponds, safeguarding water sources, enhancing cultivation methods, and constructing irrigation canals as key priorities for adapting to water scarcity.

5. Policy implications

Based on the results from the study area, local experts and stakeholders prioritize straightforward and well-established adaptation strategies that do not depend heavily on external investment. The findings suggest that many of the selected high-priority adaptation options involve minimal technical, social, or organizational complexity, or exhibit high feasibility. However, it is evident that prioritizing options that meet a set of criteria enhances the likelihood of successful implementation and gradual development. Long-term adaptation planning necessitates measures to simplify the complexity of climate adaptation options (Acharjee et al., 2020).

Techniques such as pest and disease management play a critical role in mitigating the impacts of climate change on agriculture. While this method meets all evaluation criteria, its environmental impact may vary, presenting certain limitations. Therefore, among pest and disease management methods such as biological control of the cereal cyst nematode prioritizing those with the least adverse environmental side effects in arid and semi-arid of the study area is crucial for effectively addressing water scarcity and drought.

Long-term adaptation planning necessitates measures to simplify the complexity of climate adaptation options (Acharjee et al., 2020). Pest and disease management techniques play a crucial role in averting widespread vulnerabilities in farming. While this method meets all evaluation criteria, its environmental side effects, such as its impact on reducing greenhouse gases, can vary, highlighting certain limitations. Therefore, prioritizing pest and disease management methods with the least adverse environmental effects, such as biological control of the cereal cyst nematode, which is recommended for the study area amidst climate change, is essential to effectively combat water scarcity and drought. Furthermore, agriculture service training programs should emphasize cost-effective approaches, recognizing the challenges faced by farmers in the study region who may struggle with high adaptation costs. Establishing institutional and local partnerships can facilitate the development and dissemination of adaptation methods, enhancing their adoption and implementation at the grassroots level.

Utilizing these findings, policymakers can identify criteria with low scores and address their limitations. By focusing on methods that are lower in priority (ranging from rankings 4–10 in farm management, for instance) and addressing the drawbacks associated with these methods, rankings can be improved. For instance, the land integration method, ranked sixth, could be elevated to a higher priority if weaker criteria, such as the costs of land integration and methods to reduce these costs, are addressed.

Many current agricultural management practices in each of the three categories of this study can be optimized and scaled for advanced adaptation. Utilizing these findings, policymakers can identify criteria with low scores and address their limitations. By focusing on methods that are lower in priority (ranging from rankings 4–10 in farm management) and addressing the drawbacks associated with these methods can be improved. For example, the land integration method, currently ranked sixth, could be prioritized more highly if weaker criteria, such as the costs associated with land integration and methods to reduce these costs, are addressed. To achieve this, training programs can be developed in agriculture centers to educate farmers on the benefits of land integration, such as increased income and enhanced sustainability. These programs would equip farmers with the necessary knowledge and skills to effectively implement and maintain integrated land management systems.

In the research areas, strategies such as lining canals or employing nylon covers on earth canal floors to mitigate water loss and evaporation demonstrated higher social feasibility than technical and institutional feasibility. However, the technical feasibility score for weed control was notably lower compared to the social and institutional feasibility scores. Therefore, agricultural agents can enhance farmer training in these regions by prioritizing education on various weed control methods. This targeted approach ensures alignment with the unique needs and environmental conditions characteristic of arid and semi-arid landscapes.

6. Conclusions and limitations

Successful adaptation strategies must prioritize reducing vulnerability, while establishing connections with socioeconomic and environmental processes. These strategies should emphasizeefficacy in reducing harm, cost-effectiveness of adaptation, minimal institutional, technical, and social complexity, traditional acceptance, flexibility to accommodate farmers need, and mitigation of adverse environmental impacts, including greenhouse gas emissions. The results of this study, based on these criteria, directly contribute to informing support policy design and decision-making in addressing the effects of climate change. This study underscores the importance of policy and macro interventions aimed at adapting to climate change, necessitating dialogue and stakeholder engagement for effective implementation.

The findings can be summarized as follows: (i) Relay intercropping, change of crop type, and mixed intercropping emerge as the top three priorities for crop management. (ii) Pest and disease management, weed control, and crop rotation are identified as the three main priorities for farm management. (iii) Canal lining and laying nylon on the earth floor of irrigation canals, piping water to the field instead of using soil canals for irrigation, and increasing the time intervals between irrigations were identified as the top three priorities for water management. These measures warrant significant attention from agricultural extension services. However, the study also highlights that certain adaptation methods should be avoided altogether, such as summer plowing, changing plot size (reducing the length and width of the plot), and altering planting dates. These examples represent approaches that may not have been successful in the past or could pose additional threats, such as investing resources in ineffective training methods.

While this study provides valuable insights, it is important to acknowledge several limitations inherent in the methods employed. Firstly, the participation of exclusively qualified experts from the Agricultural Jihad Organizations in the center of Khuzestan province might restrict the generalizability of the findings. Although these experts possess robust knowledge of climate change and adaptation, their input may have been influenced by the specific geographic context in which they operate. Future research could benefit from broadening the participant pool to include experts from diverse regions, thereby capturing a more comprehensive range of perspectives.

Secondly, the limited number of participants, albeit highly knowledgeable, poses a potential constraint on the study's findings. Therefore, we recommend that future studies aim to expand the sample size by including a more diverse group of agricultural experts.

A third limitation of this study is the lack of consideration for farmers' perspectives. In many developing countries, including Iran, policies and initiatives are often formulated without adequate consultation with smallholder farmers. To address this gap, future studies should endeavor to incorporate the perspectives and preferences of farmers. Understanding the disparities and agreements between the priorities of agricultural experts and farmers is essential for developing adaptation strategies that are inclusive and responsive to diverse stakeholder needs.

Lastly, the criteria used for evaluation in this study may not encompass the full spectrum of considerations relevant to policymakers. While qualitative and output-oriented criteria were employed, future research should adopt a more comprehensive approach. This includes integrating quantitative criteria and examining both processes and outcomes to illuminate the complex pathways underlying successful adaptation strategies. By broadening the scope of evaluation criteria, researchers can offer policymakers a more nuanced understanding of the multifaceted nature of adaptation processes, thereby facilitating the design of more effective and sustainable interventions.

CRediT authorship contribution statement

Tahereh Zobeidi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Masoud Yazdanpanah:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Nadejda Komendantova:** Writing – original draft, Validation, Writing – review & editing, Methodology. **Katharina Löhr:** Writing – original draft, Methodology. **Stefan Sieber:** Methodology, Validation, Writing – review & editing.

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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